

ACTIVE
MATERIALS &
STRUCTURES
LABORATORY

Development of a Solid-State Micro Hydraulic Energy Harvesting Mechanism

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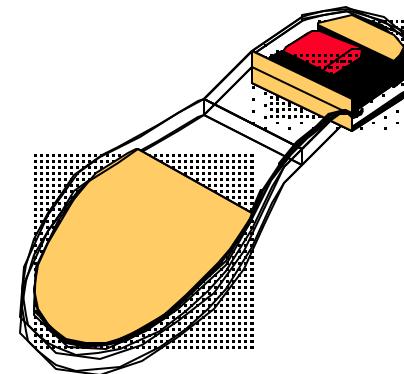
Program Goals/Objectives

Objective

- To develop a solid-state microhydraulic energy harvesting device that generates energy from low frequency pressure/stress oscillations
- Heel-strike device

Motivation: Merging Technologies/Ideas

- Solid-state transducer (active) materials
- MEMS micro-fabrication techniques
- Hydraulic-mechanical power conversion



Potential Applications

- Heel-strike power harvester (extract energy from human movement)
- Combustion power generator
- Other potential energy sources (chemical/thermal gradients, vibration, wind, fluid flow)
- Actuator

Motivation

Piezoelectric Materials

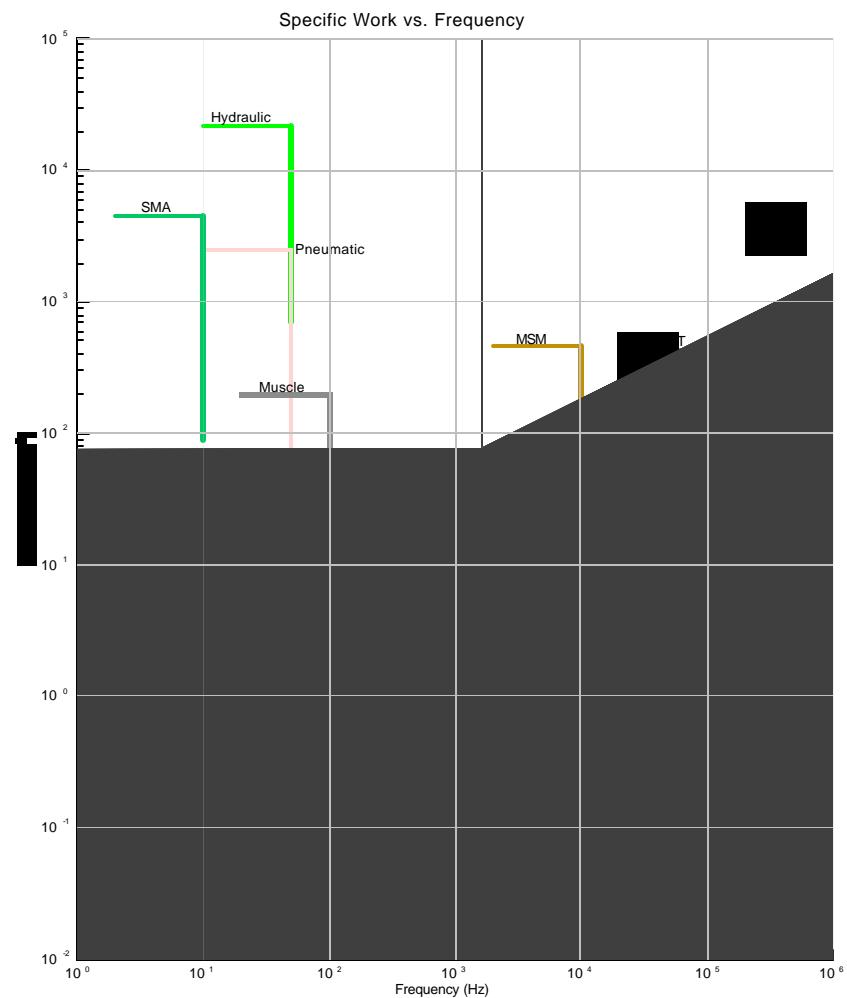
- High specific power (peak power densities ~ 100-10000 kW/kg)
- Transducer Performance Metric
Specific Power = [single stroke specific energy] x [bandwidth]

MEMS: “Microscale Devices”

- High structural natural frequencies
- Scaling limits in fluid systems due to increased fluid viscous losses

Microhydraulics

- Conversion of mechanical power to fluid power at the microscale, and vice-versa
- Flexible system architecture conducive to micromachining technologies (channels, ducts, cavities, etc.)



Heel-Strike Potential/Early Design

Vertical ground force :

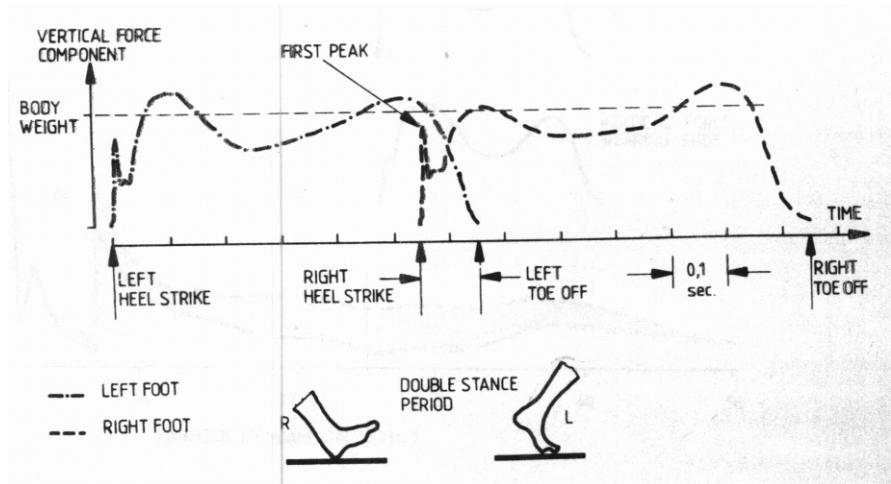
0.6~1.2 body weight with 0.5~0.6 sec duration

Cadence :

1~1.5Hz (moderate gait: 55-90 steps/min)

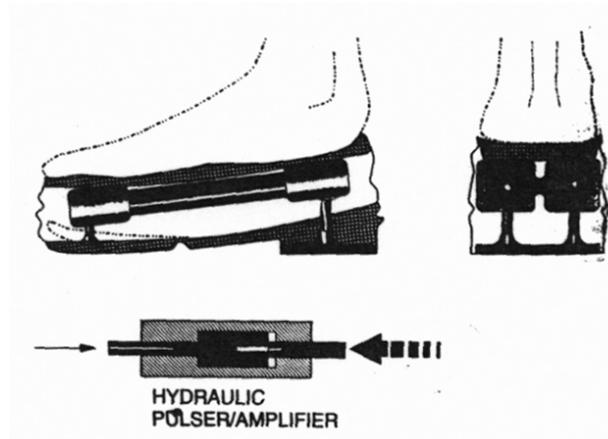
Mean power :

8~10W per foot (for 70 kg person, with 1cm stroke)



Gait-powered battery charging system

(used to power artificial organs, Antaki et al., 1995)



Background

Piezoelectric Power Generators

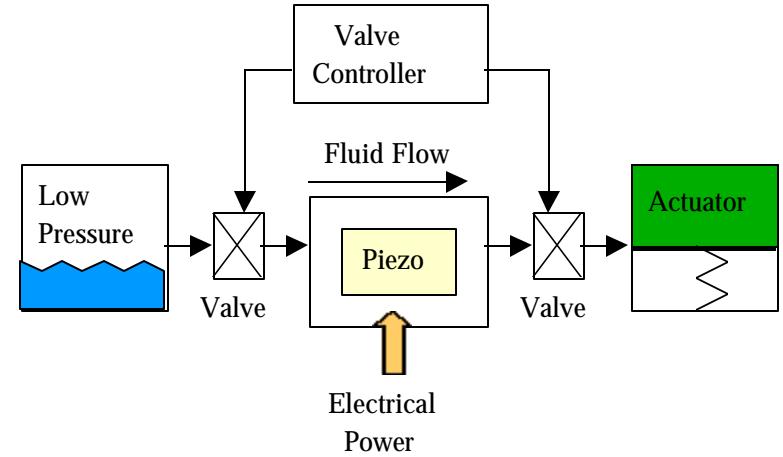
Piezoelectric Power Generators

- Large number of macroscale piezoelectric power generator concepts exist
 - *Walker self-generating power source*: piezoelectric film converts pressure pulse of walker's foot into electrical pulse signal [Wang, 1991]
 - *Ocean wave energy conversion*: floating buoy anchored to sea floor strains a piezoelectric member, current is rectified [Burns, 1987]
 - *Portable electronic generator for timepiece*: motion induces rotation of wheel with attached piezoelectric elements; during rotation elements are impacted, current is rectified [Yamashita, 1978]
 - *Piezoelectric induced battery charging system*: alternating magnetic field vibrates piezoelectric element, current is rectified [Schroepel et al., 1998]
 - *Piezoelectric power generator for electronic device*: motion induces vibration in lever arm; arm strains piezoelectric elements, current is rectified [Takahashi, 1998]
 - *Cylindrical stator piezoelectric energy generator*: armature with piezoelectric liner rotates within stator, thereby compressing piezoelectric material; current is rectified [Epstein et al., 1996]
 - *Vehicular mounted piezoelectric generator*: piezoelectric elements attached to tires are compressed upon tire rotation, current is rectified [Triplett, 1985]
- No MEMS piezoelectric power generators

Actuator/Power Generator Concepts

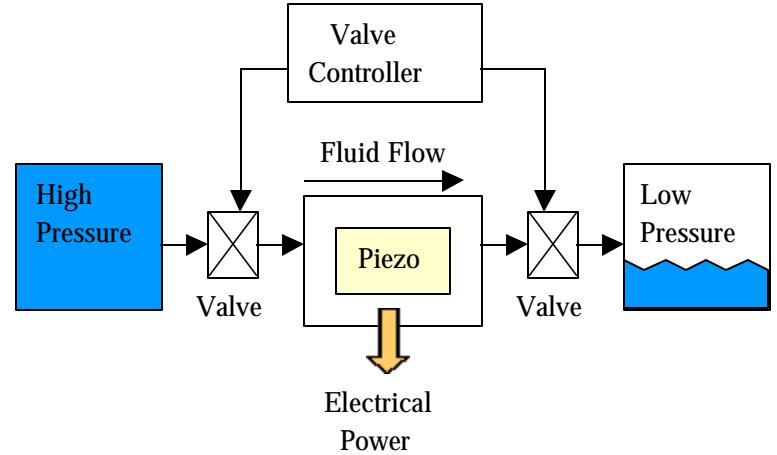
MHT Actuator

- High frequency electrical excitation of piezoelectric material
- Active valves
- Large stroke, low frequency output actuation



MHT Power Generator

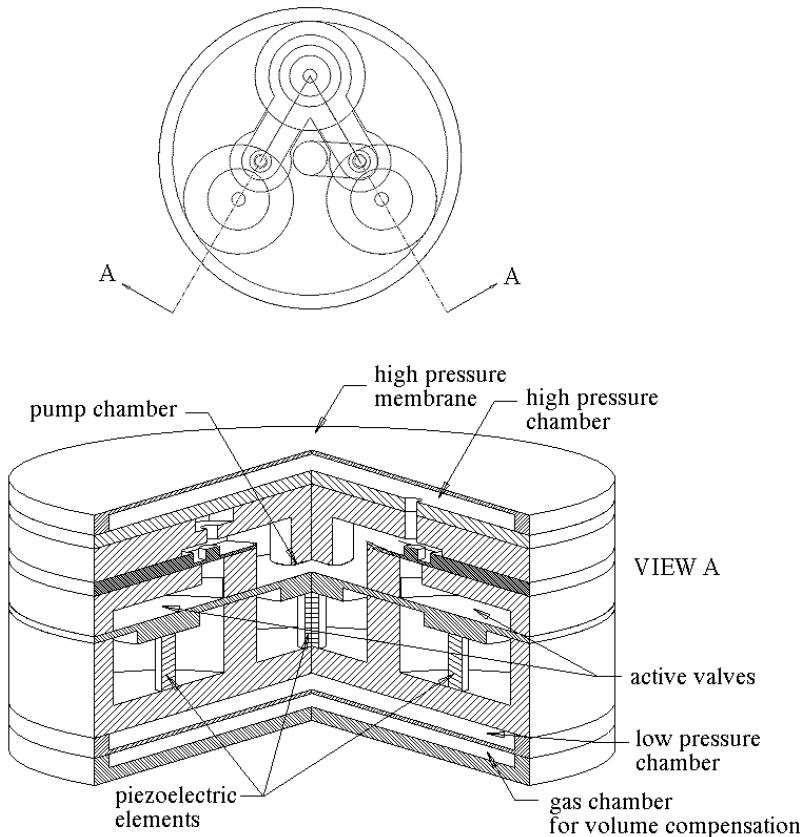
- Static high pressure fluid source
- Active valves
- Pulsed mechanical excitation of piezoelectric material
- Rectification/storage of electrical power



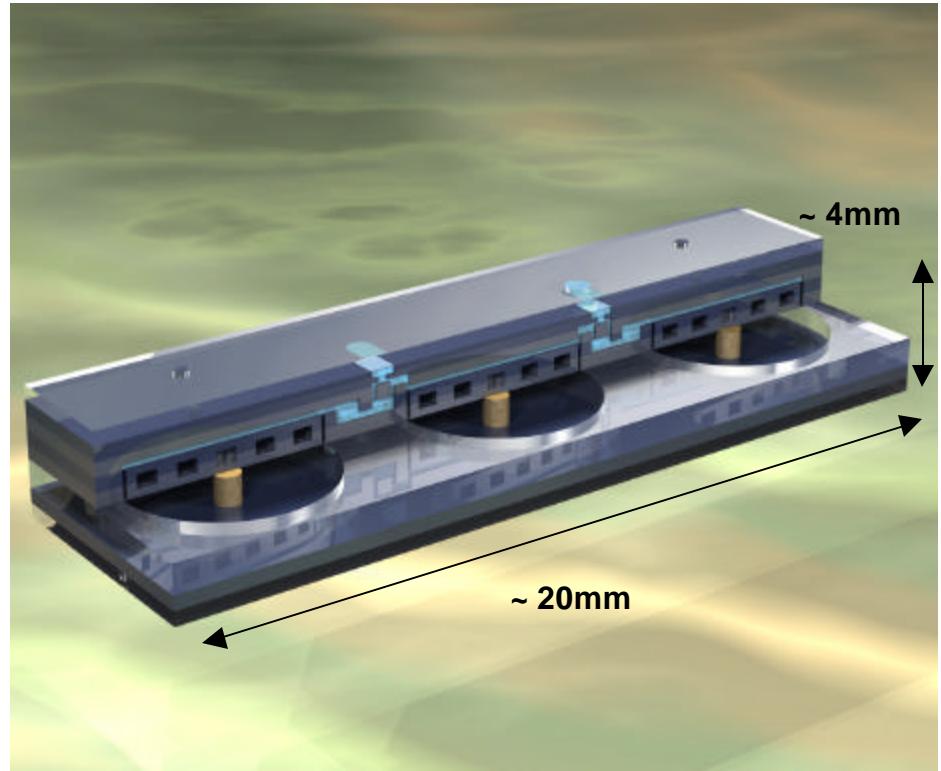
MHT System Arrays

- Parallel or series combinations depending on output requirements

Generic Configuration of MHT Device

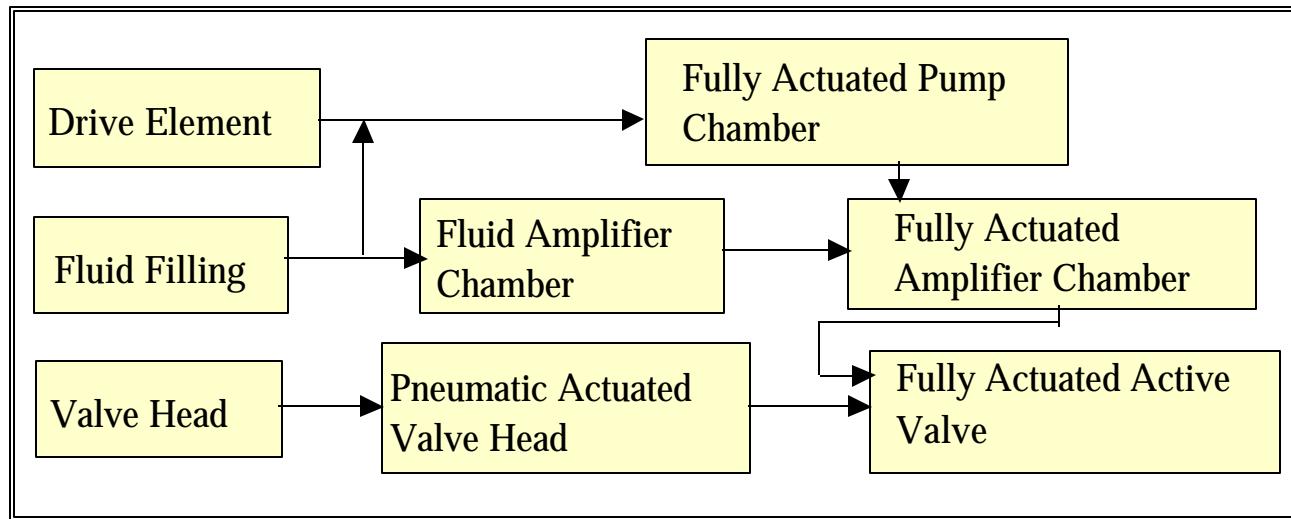


Pump/Generator Chip



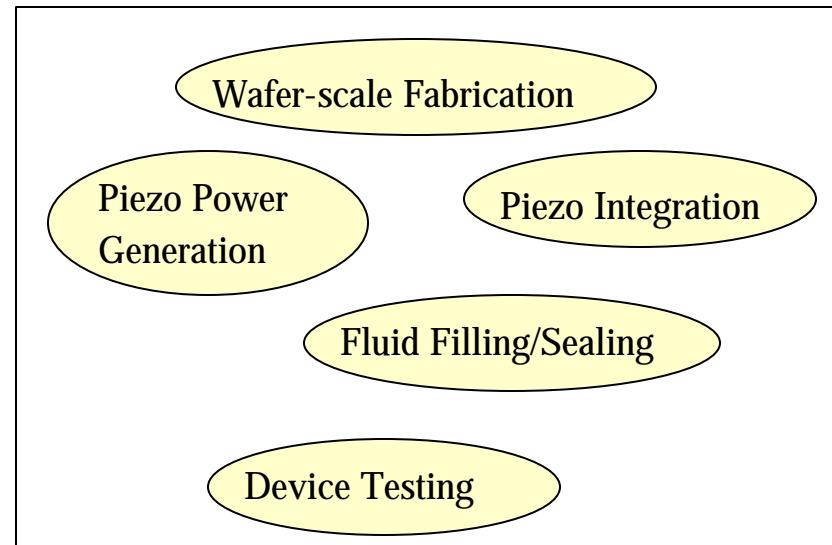
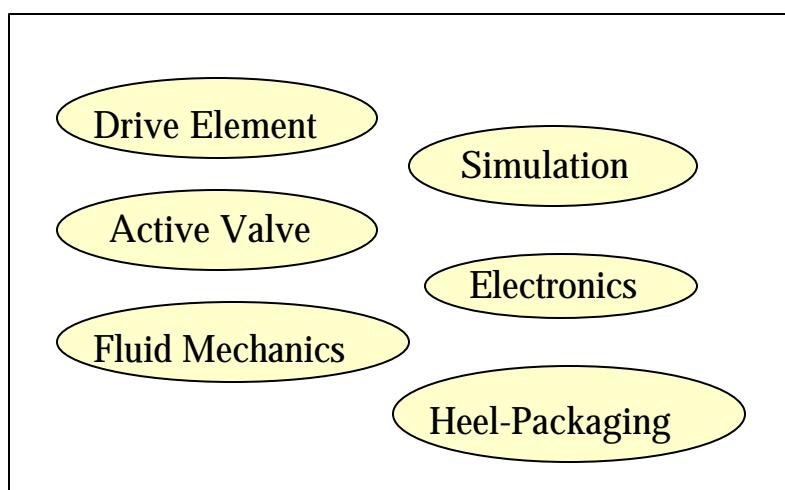
Program Plan

- Design, Fabrication, and Testing of Primary Components
 - Piezoelectric Drive Element Device
 - Pump Chamber, Fluid Amplifier
 - Active Valve
- Integration of Primary Components
- Integration with Supporting Subsystems
 - Electronics
 - Packaging



Program Plan

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Drive Element Design

Power requirement

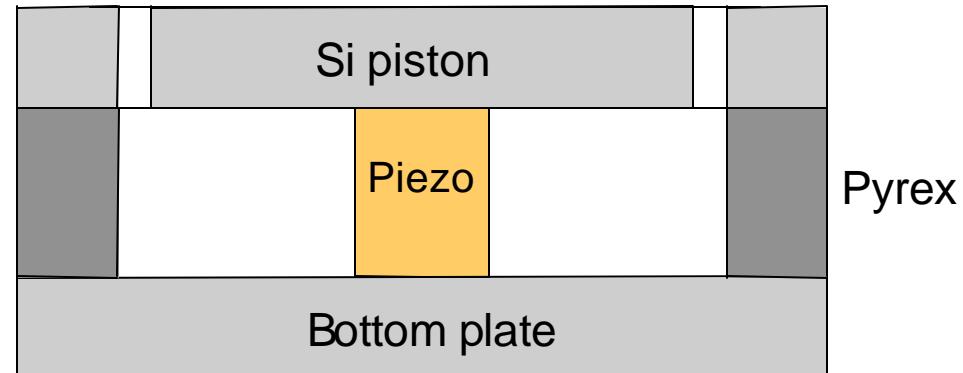
- Delivery / generation of 1 W electrical power

System issues:

- Impose functional requirements for design of other components
- Fluid, valve, packaging

Critical issues:

- Piezo coercive stress
- Structural compliances
- Structural dynamics
- High cycle fatigue



	PZT5H	PZT 5A	PZT 4	PZT 8	PZNPT
E_{S33} ($10^{-12} \text{ m}^2/\text{N}$) shunt ckt compliance	20.7	18.8	15.5	13.9	130
K_{33} coupling coeff.	0.75	0.7	0.7	0.64	0.92
σ_d (MPa) coercive stress	30	50	120	150	30(?) [*]
FOM (kJ/m ³)	2.62	5.76	27.4	32.1	26.4
normalized FOM	1	2.2	10.45	12.24	10.07

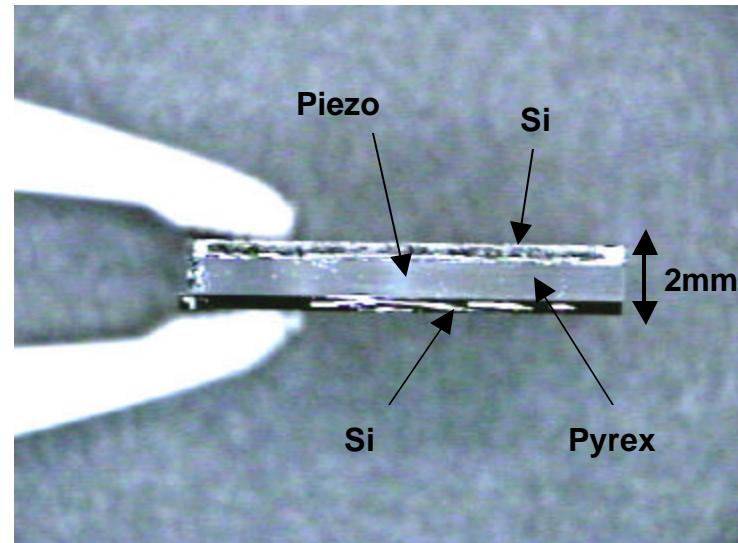
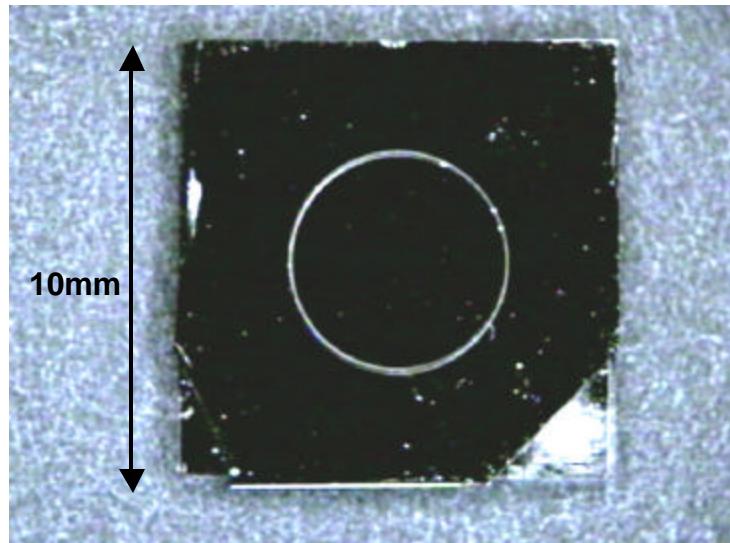
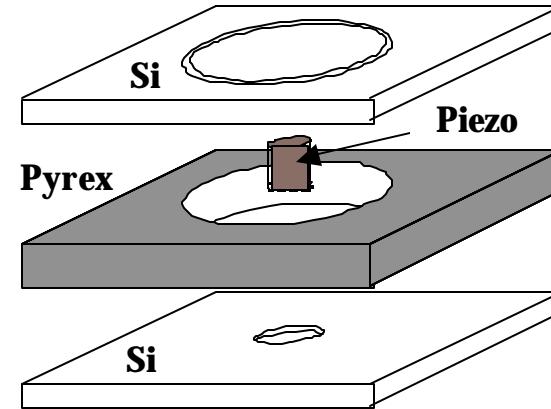
$$\text{Figure of Merit (FoM)} = s_{33}^E K_{33}^2 \sigma_d^2 / 4$$

Drive Element Component

1st-Generation Device Fabrication

Objectives

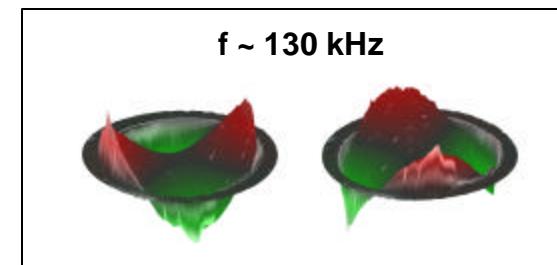
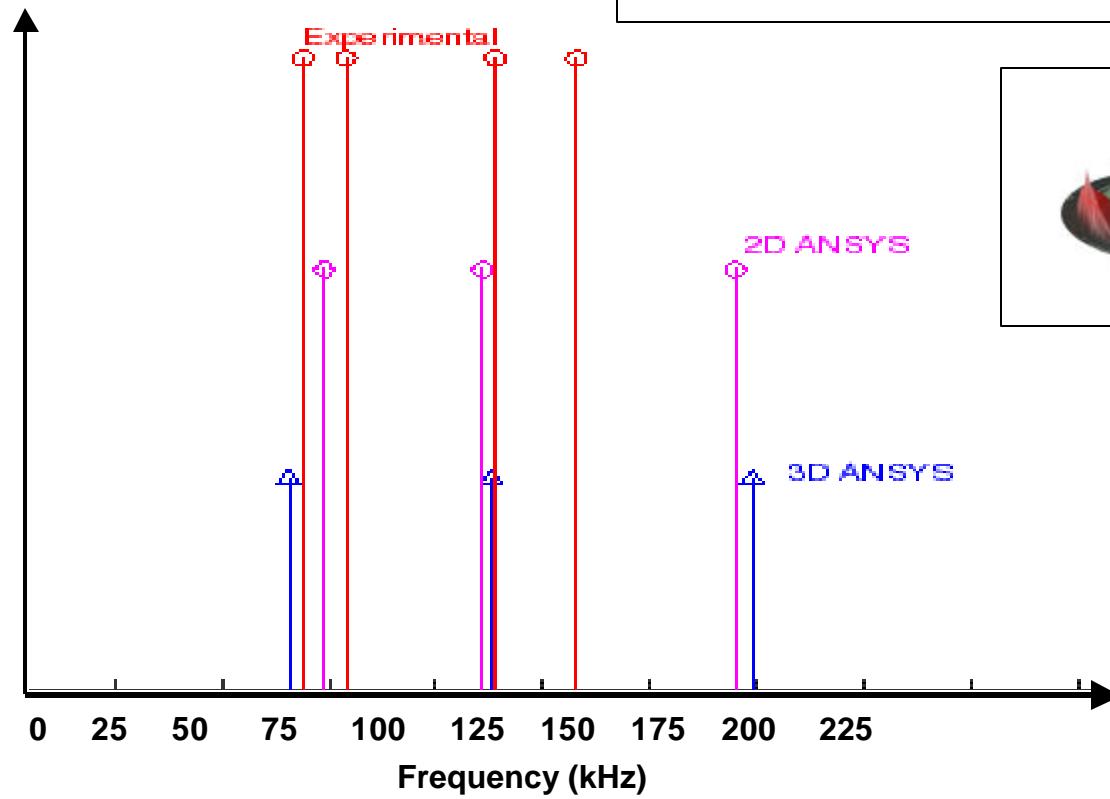
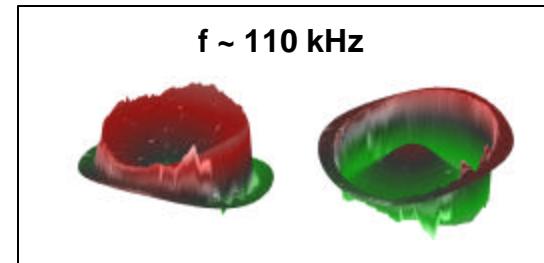
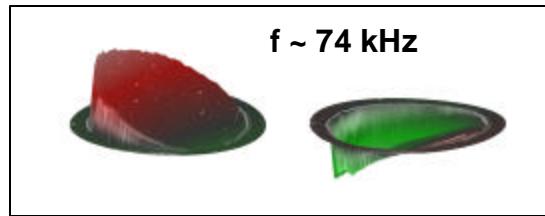
- Prove capability to integrate the piezoelectric material
- Correlation between model/experimental behavior
- Identification of unforeseen design and fabrication issues



Drive Element Component

Modeling/Experimental Results

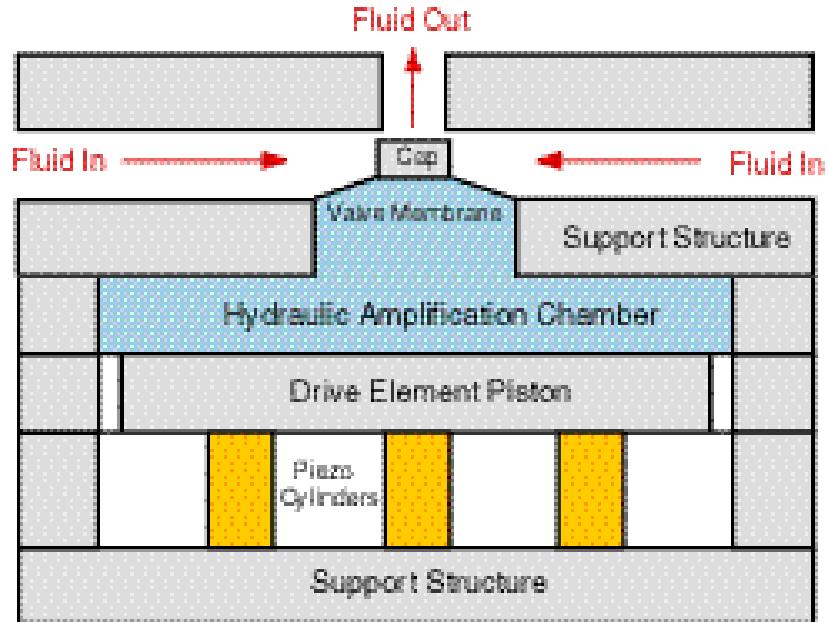
Good correlation between experimental and predicted dynamic behavior



Active Valve Design

Functional Requirements:

- Small size (~mm)
- Large stroke (40-50 um)
- Large actuation authority (1-2 MPa)
- High frequency (10-20 kHz)
- Minimal fluid losses



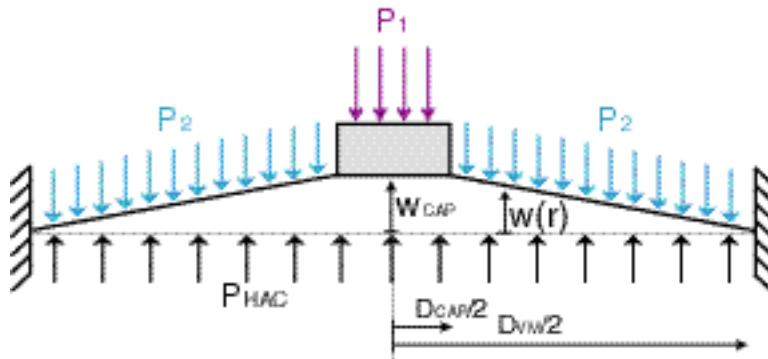
Design:

- **Hydraulic amplification** of drive element displacement → large valve stroke
- Stiff drive element and stiff fluid maintain high frequency operation

Critical Issues:

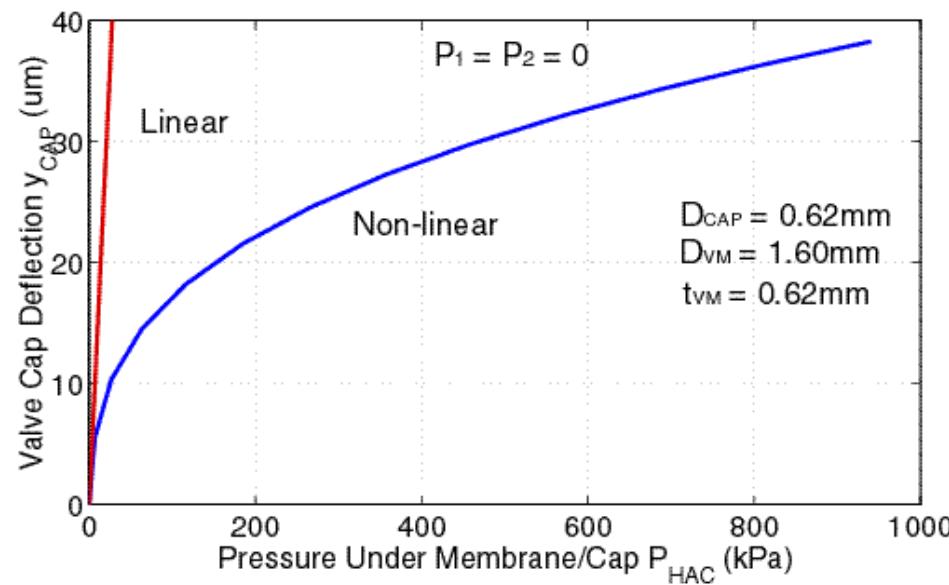
- Structural integrity of Si membranes
- Coercive stress of active material

Non-Linear Behavior of Valve Membrane



Non-linear numerical code:

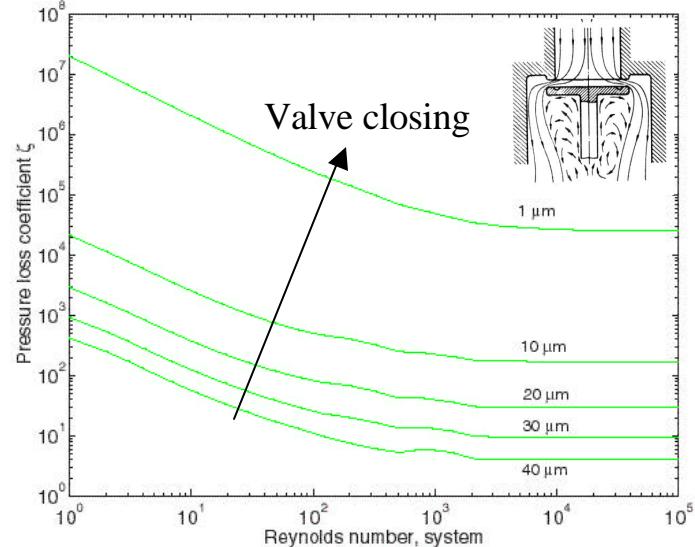
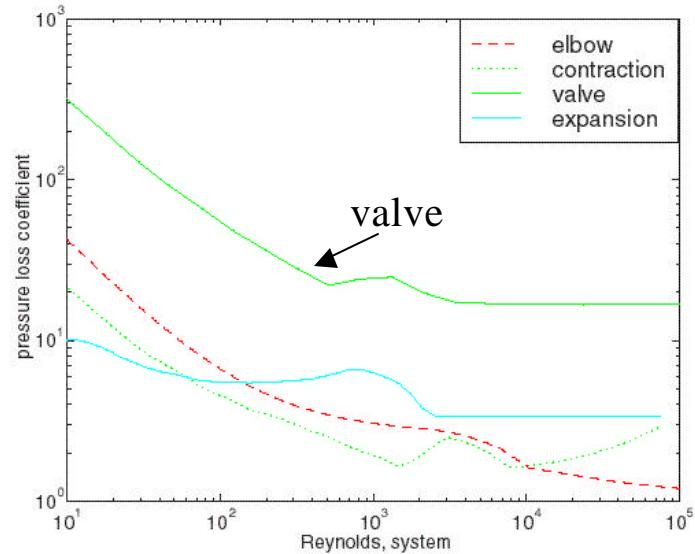
- Valve cap deflection
- Valve membrane swept volume
- Membrane stress
- Prestress effects included



*Y. H. Su, D. C. Roberts, and S. M. Spearing, "Large deflection analysis of a prestressed annular plate with a rigid boss under axisymmetric loading," ASME Journal of Applied Mechanics.

Fluid Mechanics Modeling

- Hydraulic system modeled with lumped elements
- Reynolds number varies from 1 to 20,000 with a Strouhal~1.
- Micro-valves dominate flow losses due to :
 - Short strokes
 - Fabrication process limitations
- Initially an orifice model was used as valve model
- Valve losses were characterized experimentally supported by numerical simulations and analytical models



Macro-Scale Valve Experiments

Motivation :

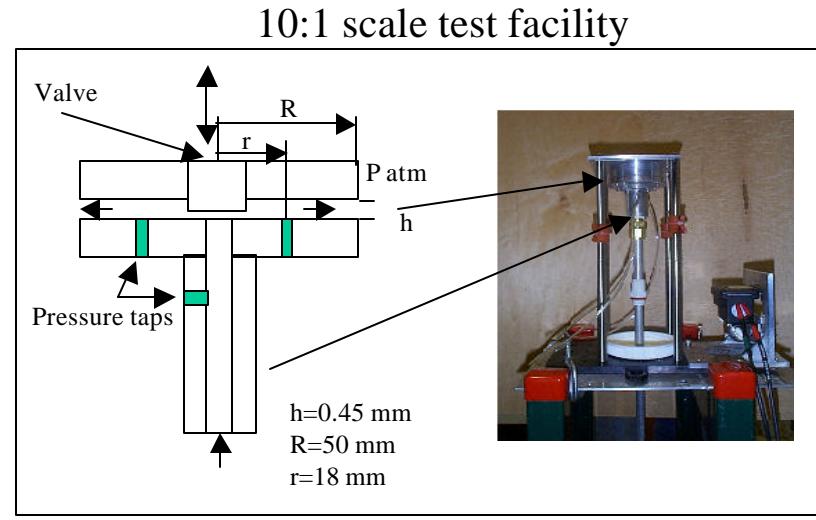
Characterize steady and unsteady state valve behavior experimentally

Results :

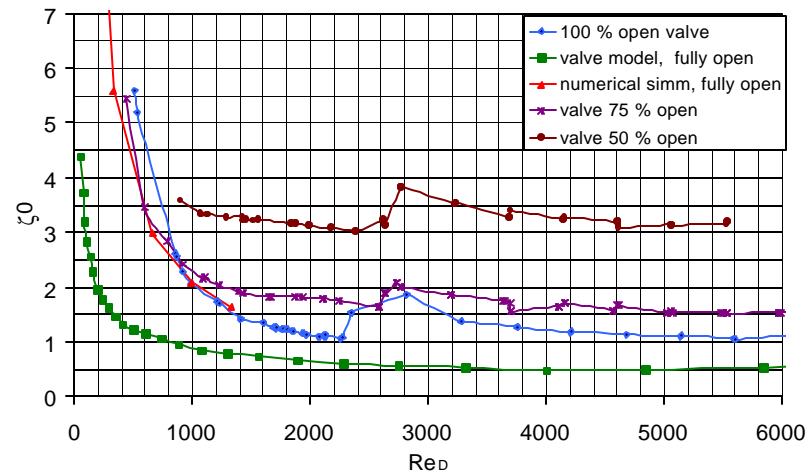
- Experiments show that the orifice model captured the correct valve behavior
- Orifice model underestimates valve losses by a factor of ~ 2 in the turbulent regime

Future work

- Parameter studies being conducted :
 - seat area
 - valve stroke
 - valve sizing,etc
- Unsteady valve experiments
- Full scale (micro-scale) experiments



Valve loss coefficients for different valve apertures.
Comparison with model and numerical simulations for fully open valve



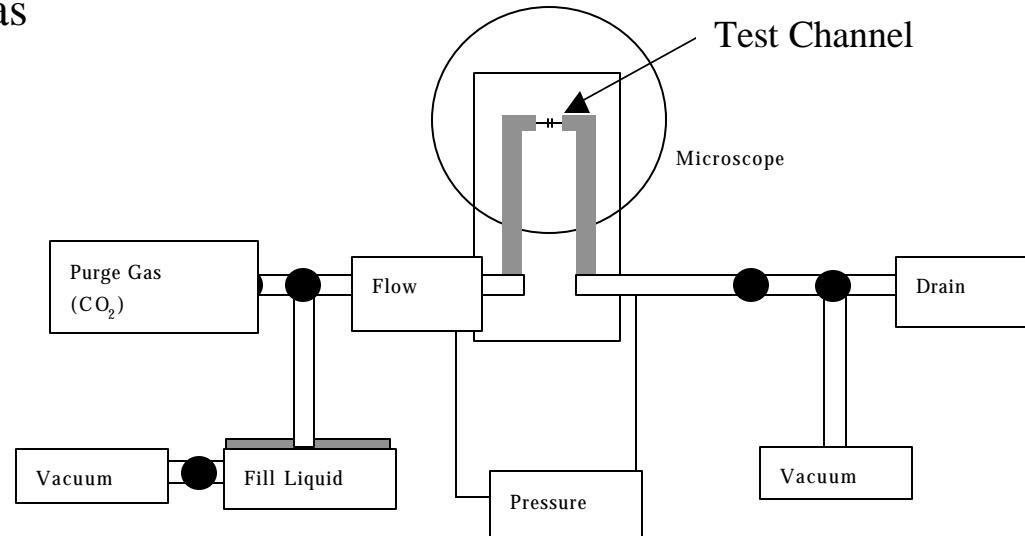
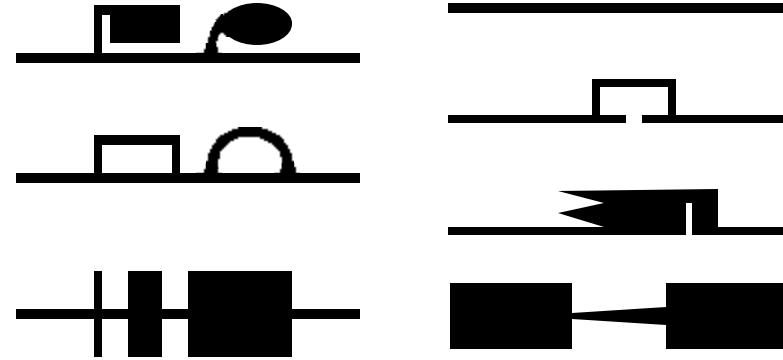
Fluid Filling Studies

Critical Issues

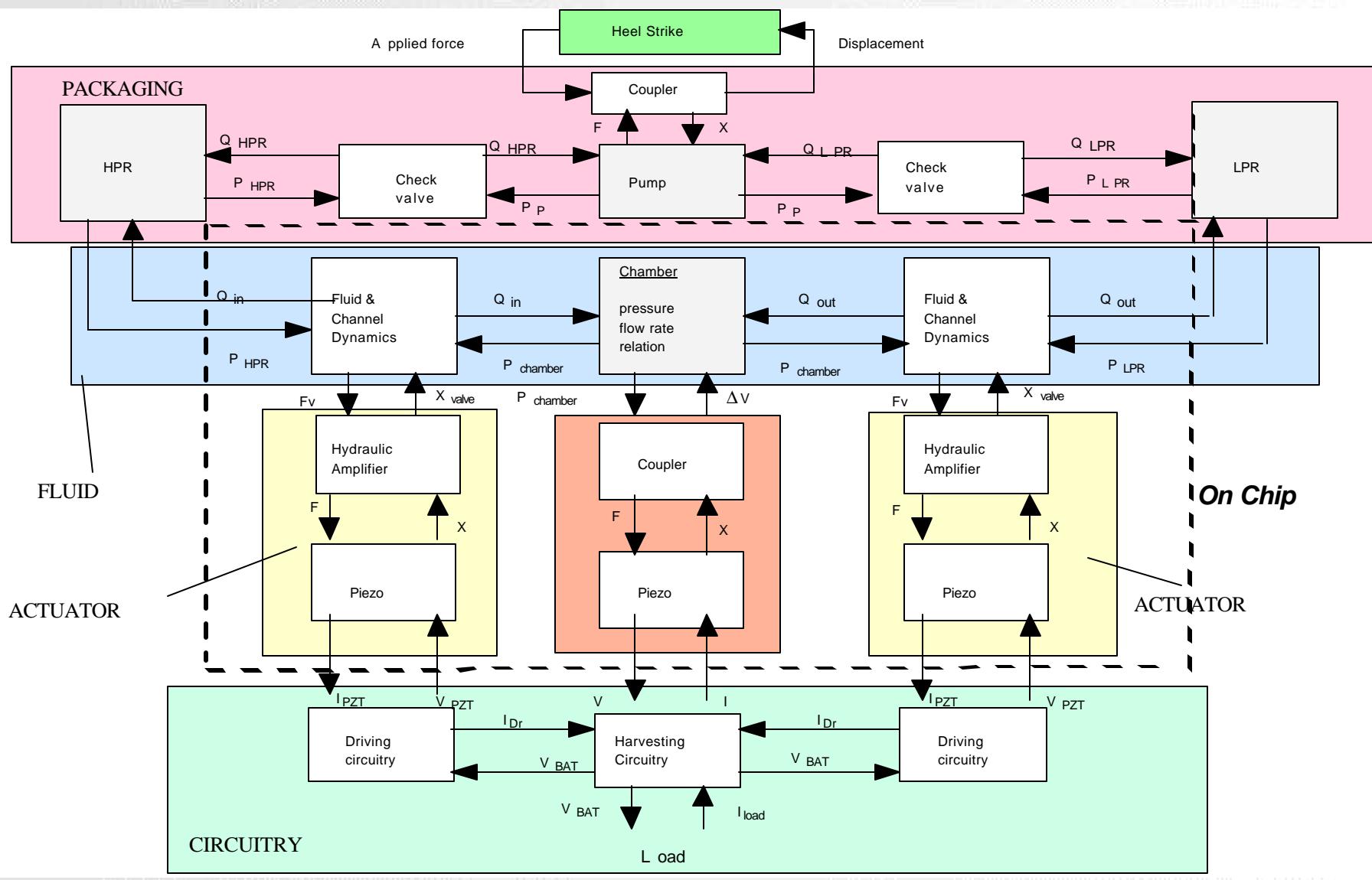
- Elimination of trapped gasses
 - During filling
 - Fluid outgassing
- Post-filling encapsulation

Experimental Approach

- Outgas liquid
- Purge system using soluble gas
- Evacuate
- Fill (pressurize)



MHT System Simulation Flowchart

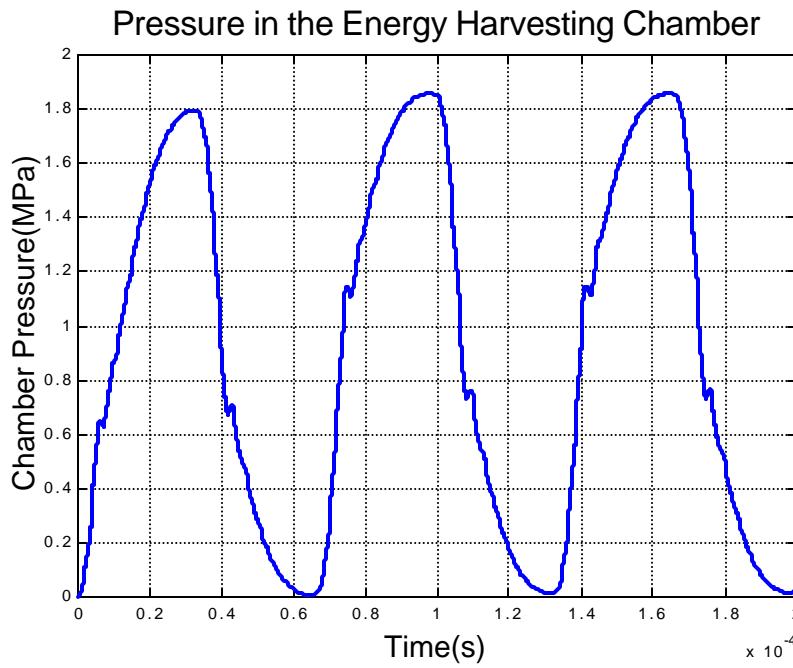


Simulation Results

- Characteristic Design Parameters for 1W -

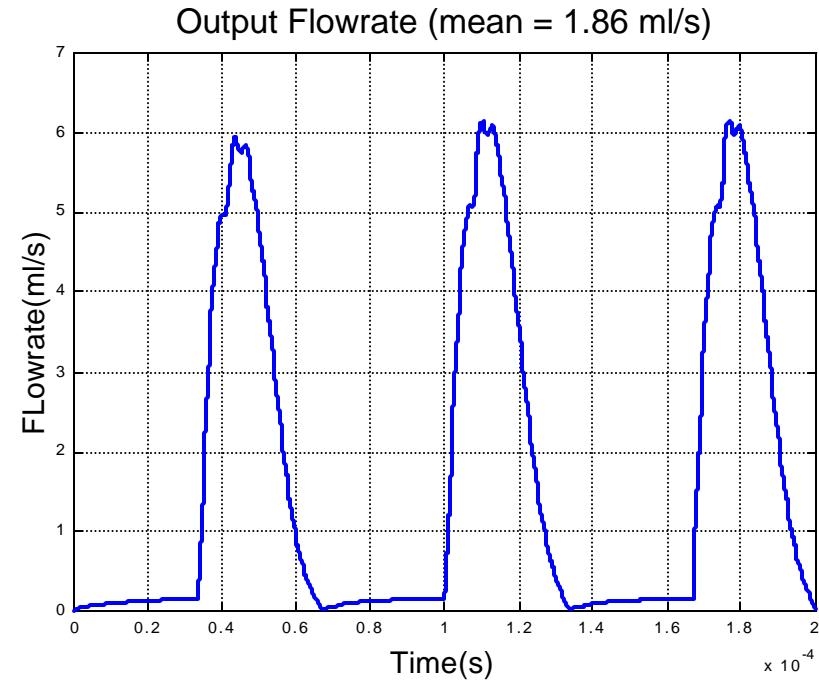
Operational Parameters:

- P-HPR = 2.2 MPa ; P-LPR = 0 MPa
- Max. Chamber Pressure = 1.875 MPa
- Mean Flowrate = 1.86 ml/s
- Max. Piezo Stress = 30 MPa



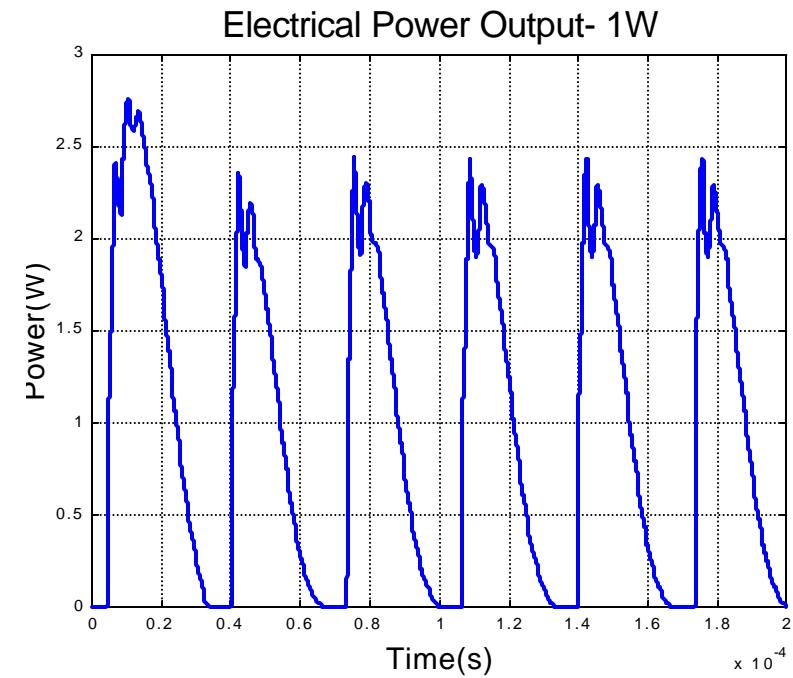
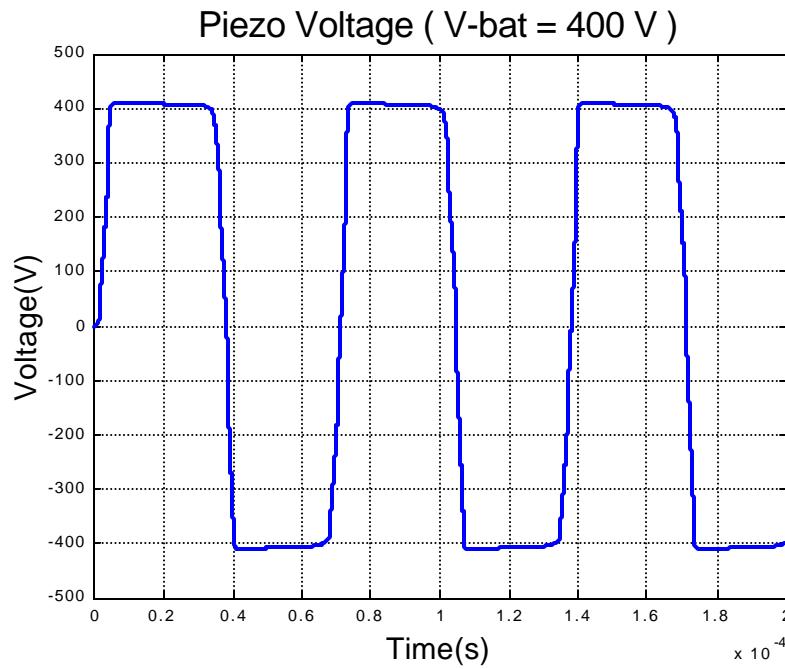
Geometric Parameters:

- Chamber Diameter = 8.4 mm
- Chamber Height = 200 microns
- Piezo Length = 1mm
- Piezo Diameter = 2 mm



Simulation Results

-Output Power and Efficiency-



Hydraulic Power Input = Pressure Differential x Net Flowrate

- Input Power = 4.1 W
- Output Power = 1 W

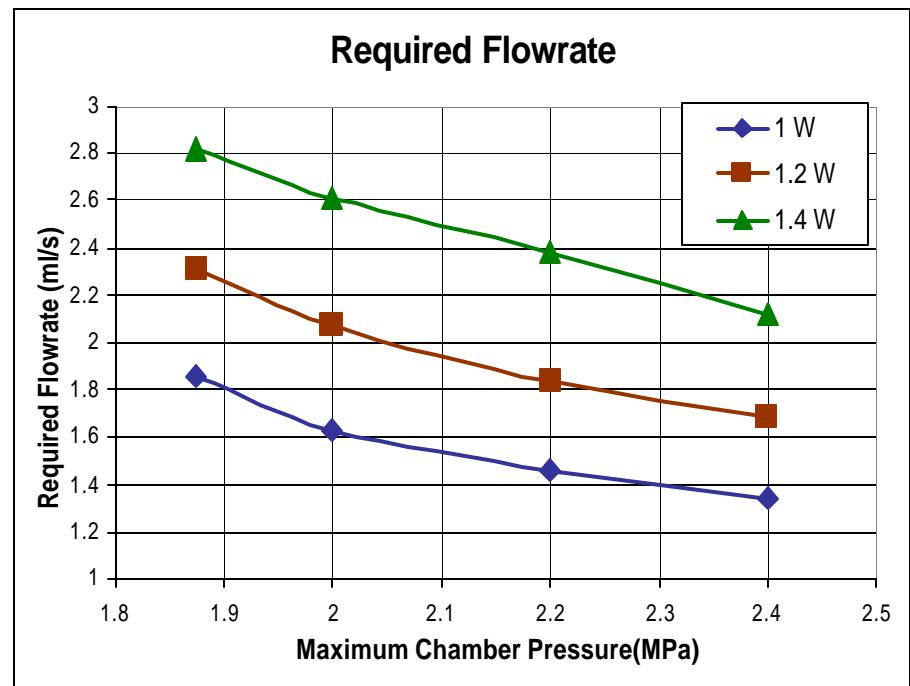
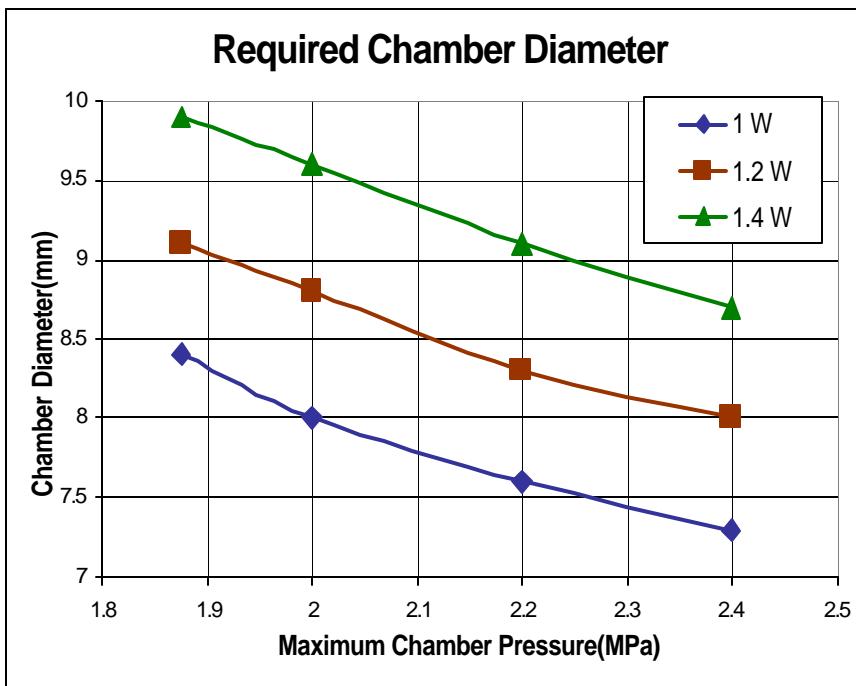


Efficiency = 24.4%

Simulation Results

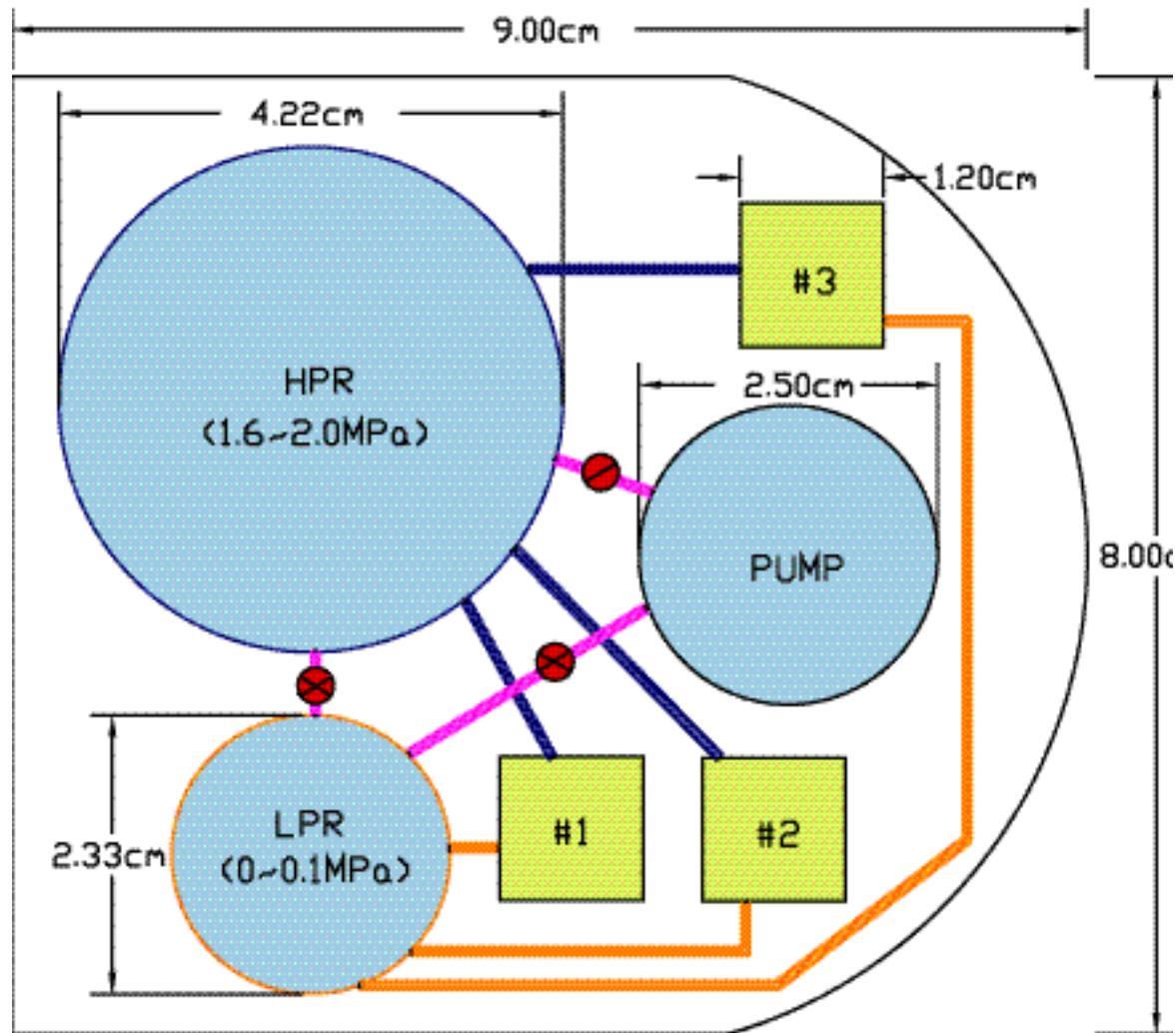
-Differing Power Requirements-

- Design parameters heavily depend on maximum allowable chamber pressure
- Tradeoff between low pressure and low flow rate



Heel Strike Package Design

- Design Flow rate: 6 ml/s
- 3 device chips within heel
- Can generate 2-3 W/heel
- Spring loaded bellows reduce pressure fluctuation



Material Test for PZT-5H Power Generation

Introduction

Motivation:

- High compression may depolarize material
- Characterize compressive drive limit

Techniques:

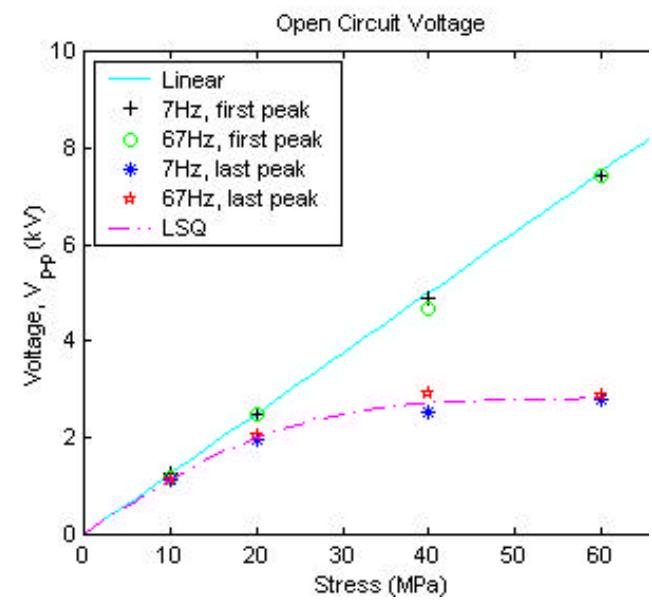
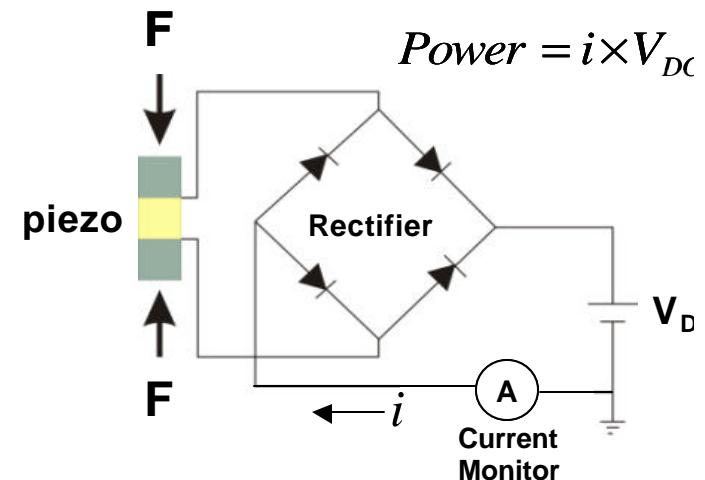
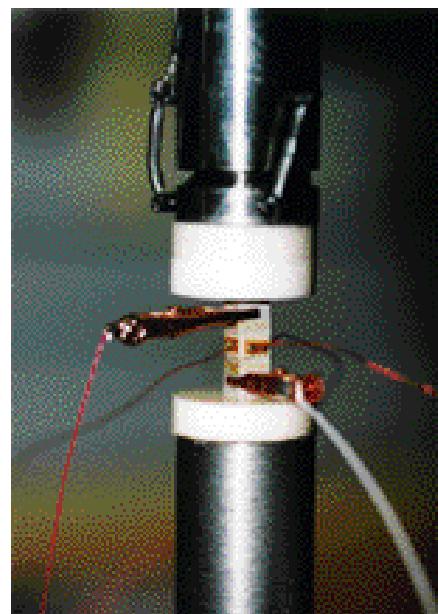
- Open circuit voltage measurement
- Power measurement using rectifier circuit

Results:

- Maximum power occurs at

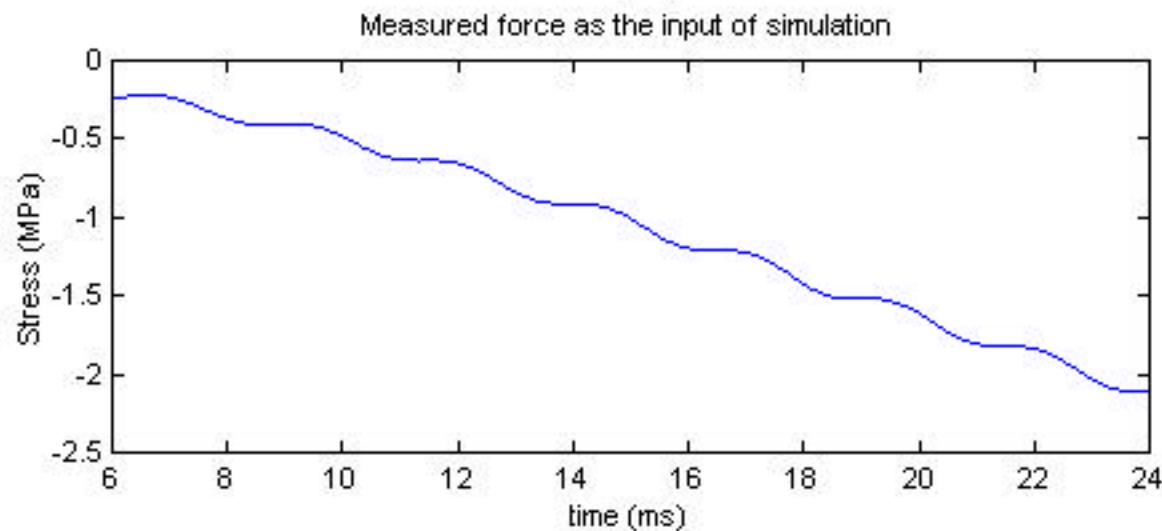
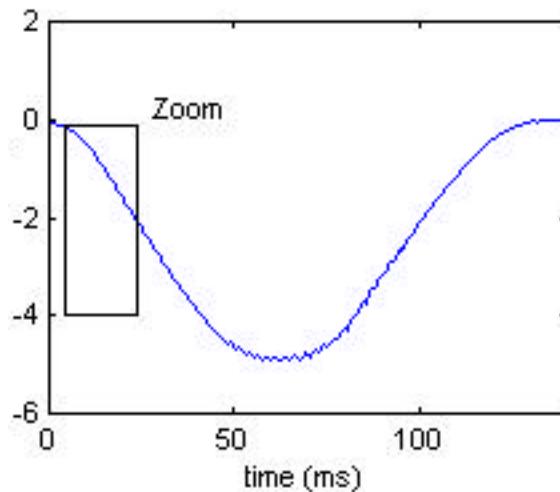
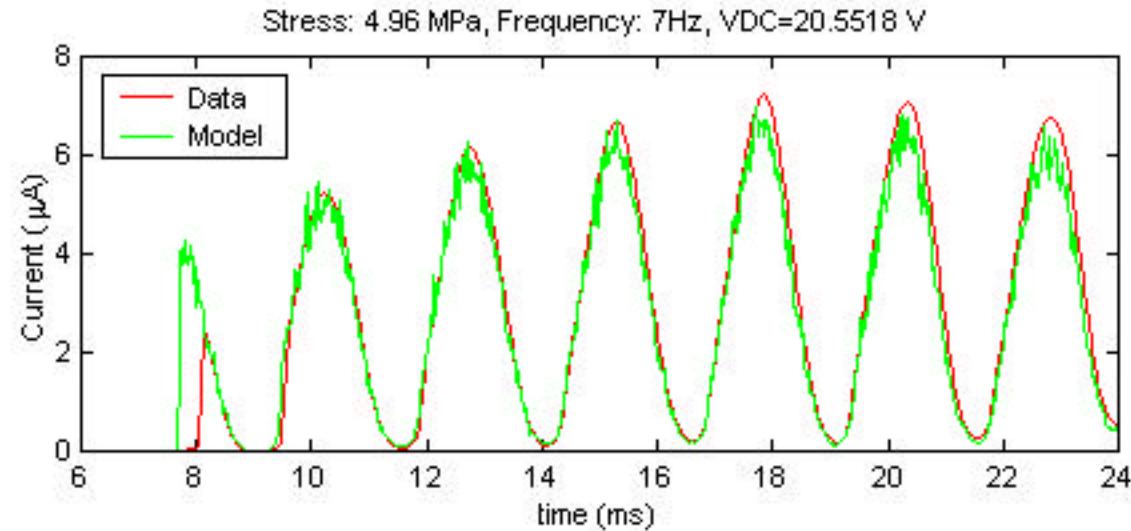
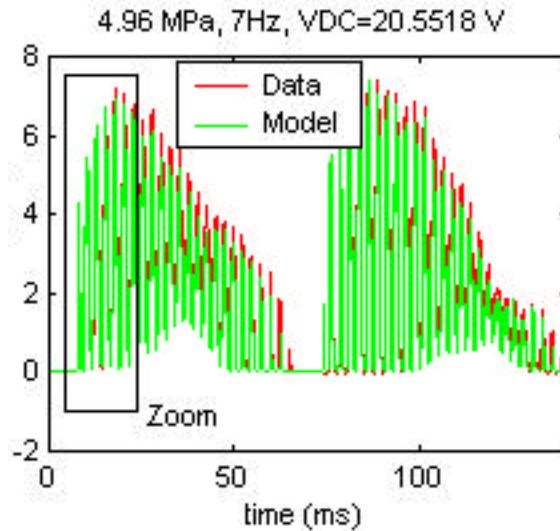
$$V_{DC} = \frac{1}{2} V_{OpenCircuit}$$

- High frequency load results in high power



Material Test for PZT-5H Power Generation

Data and Model



Material Test for PZT-5H Power Generation

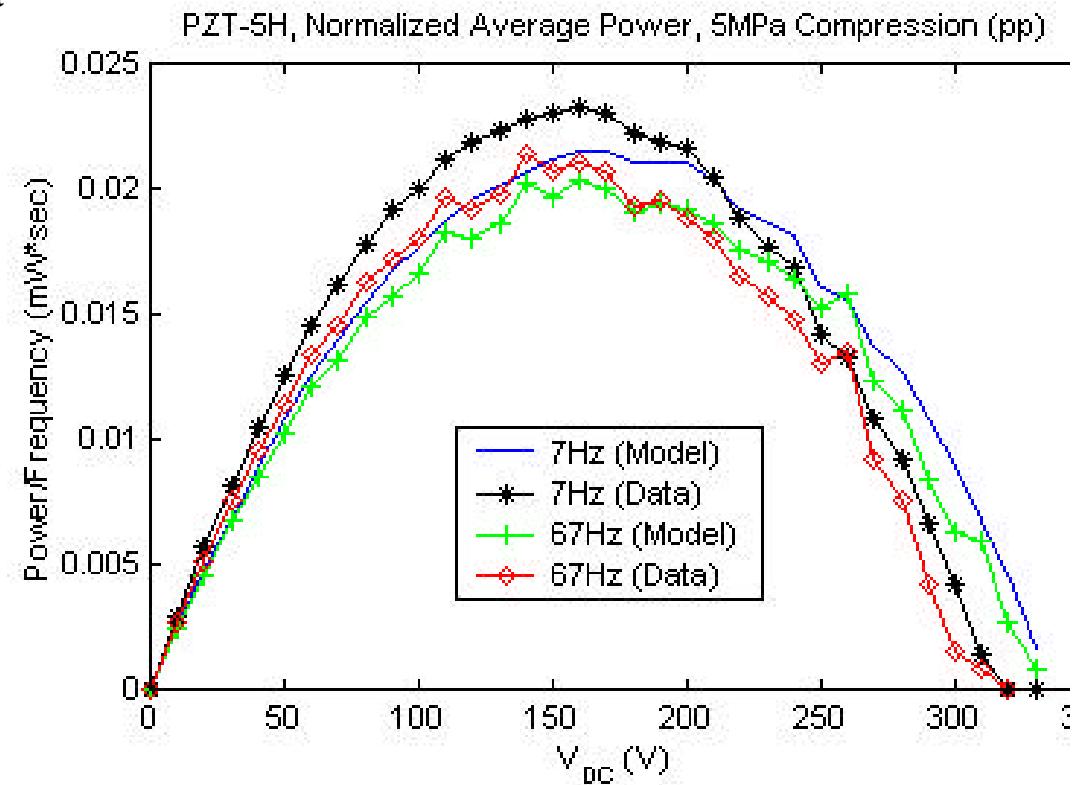
Data and Model

Power is proportional to compression driving frequency,
assuming that

- Linear coupled piezoelectricity
- Manufacturer's material data
- Exponential diode model
- Ideal battery

Future work:

- Higher load
- Higher frequency load



Device Design: Critical Issues

Piezoelectric material

- Coercive stress of PZN-PT under AC operation

Materials and Structures

- Strength and stress of silicon membrane
 - valve membrane testing
- Fatigue crack propagation in bonding
- Eutectic alloy bond

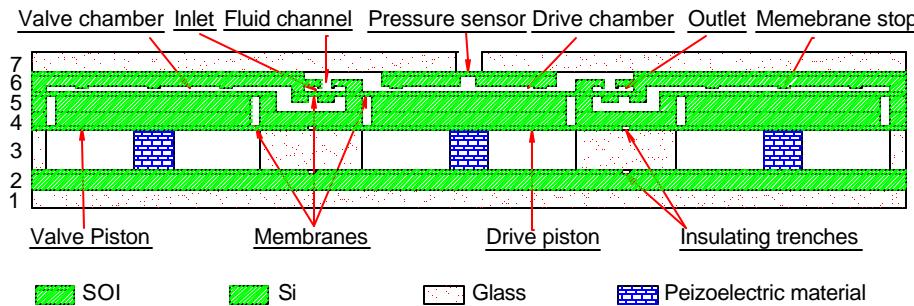
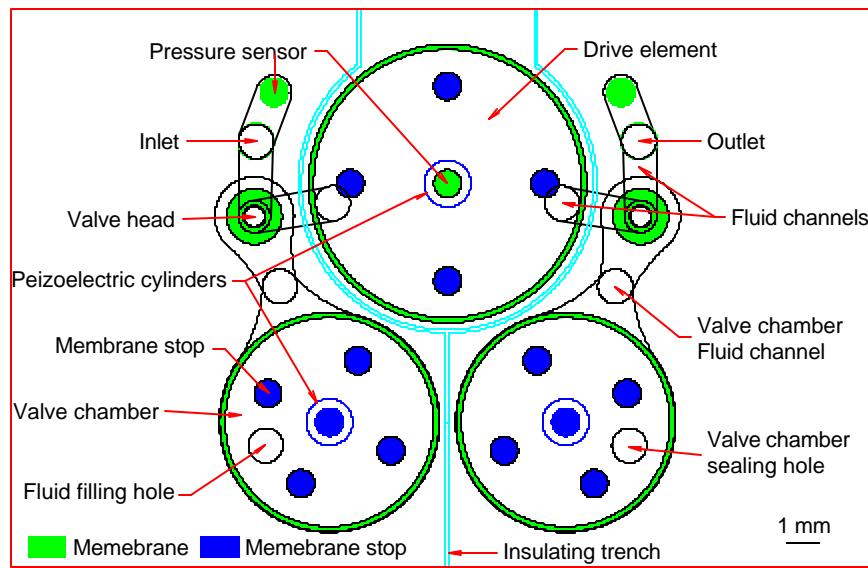
Active valve design

- Power consumption

Fluids

- Fluid loss and negative pressure
 - Experimental and numerical valve characterization
 - Fluent CFD analysis

Fabrication: Energy Harvesting Device

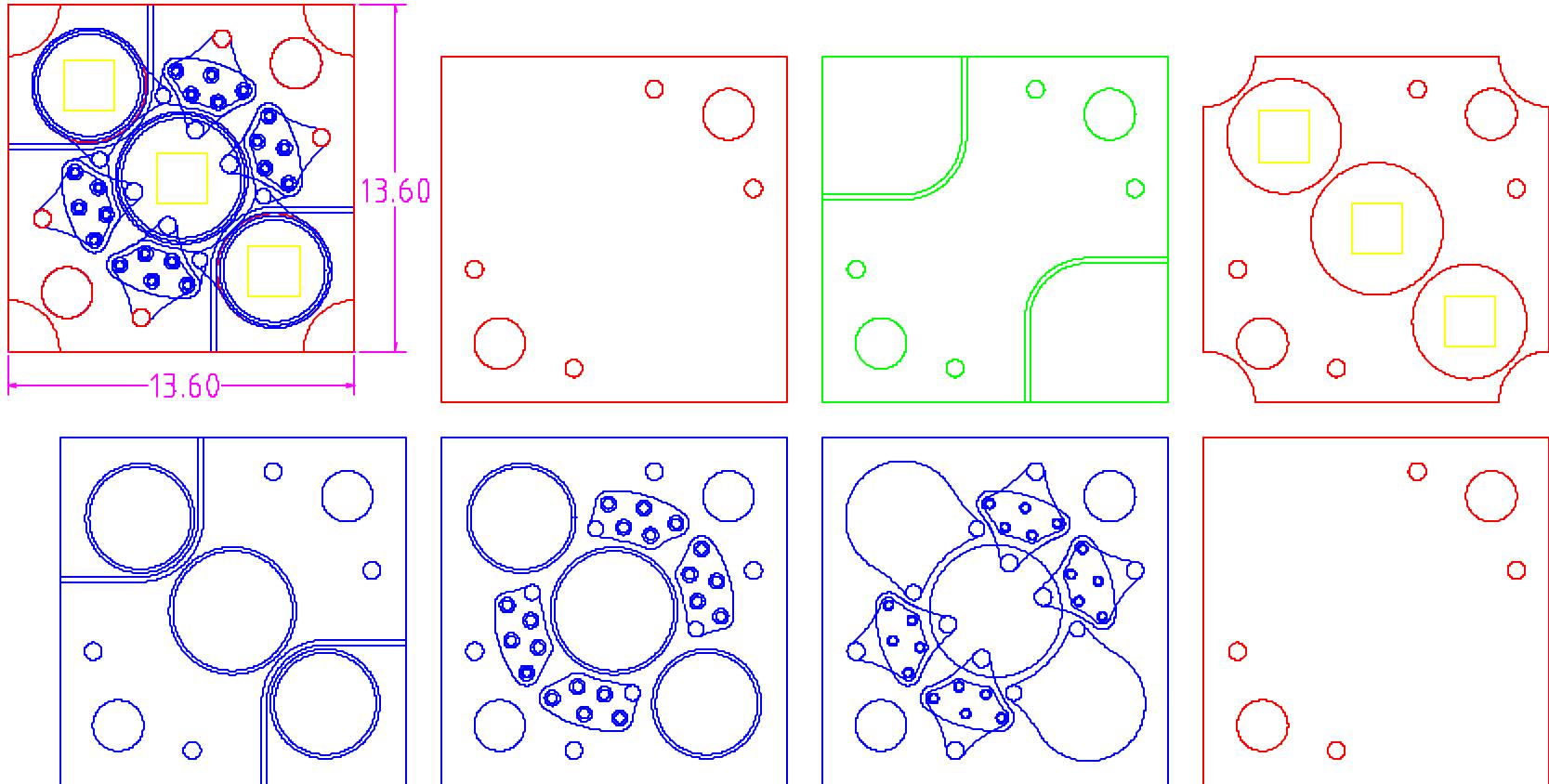


Top view: functional parts (to scale).

Side view: a zig-zag section (schematic)

Energy Harvester with Multiple Active Valves

Top view of individual layers (unit in mm)



Red: Glass

Green: Si

Blue: SOI

Yellow: Piezoelectric Material

Device Fabrication: Critical Issues

Fabrication Processes

- 2-side Lithography: no existing standard process.
- Fillet Radius Control with proof-mass: important to the membrane strength.
- Alignment: critical to valve head and positions.
- Avoid Sealed Cavities in Si-Si Bonding.

Electrical

- Separation of leads to 3 Piezos: etching through SOI.
- Insulation between layers: SiO₂ breakdown voltage $\sim 500 - 1000\text{V}/\mu\text{m}$.
- Wire path and wire bonding: additional patterning and corners sticking out.

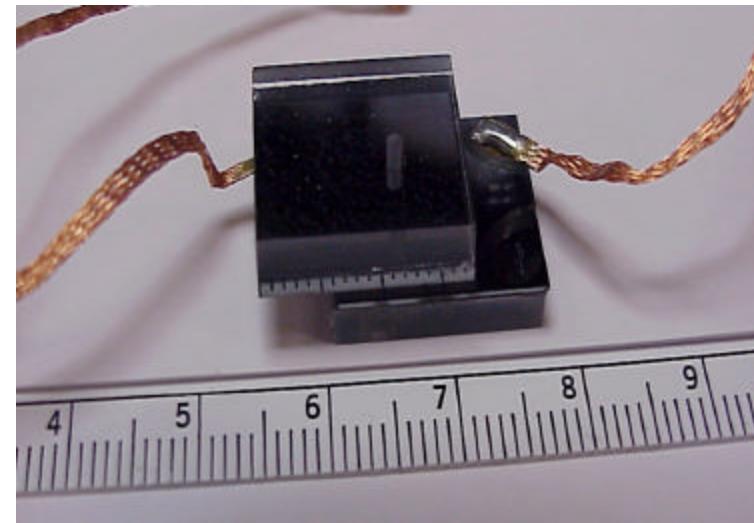
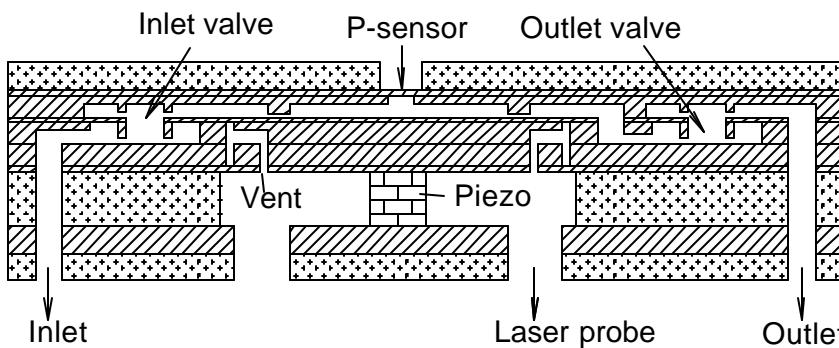
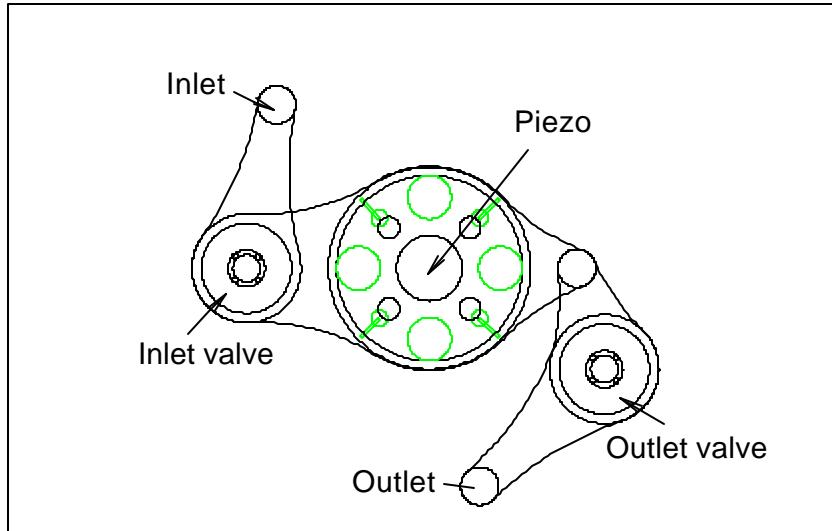
Fluid Filling

- Vertical filling channel.
- Effective sealing.

Piezoelectric Material

- Integration of piezo.
- Piezos have to be bonded on chip level at beginning.

Passive-Valve Micropump



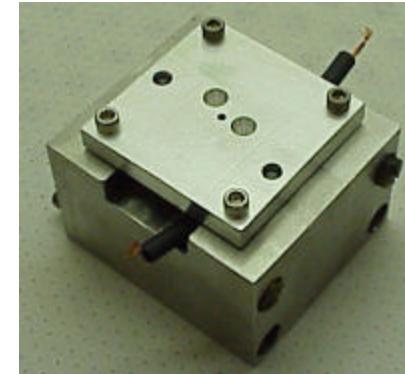
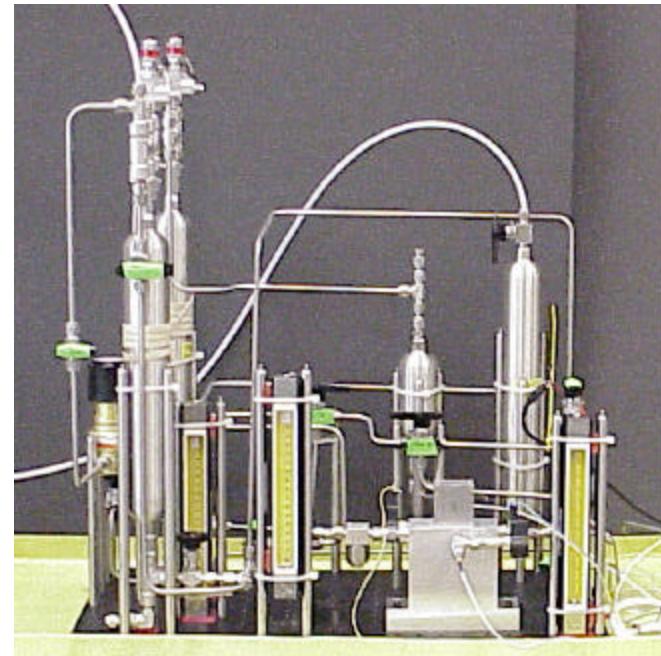
Micropump Testing

- Test setup

- Working fluid: 0.65cst Dow Corning DC200 silicone oil
- Variable bias pressure up to 850 kPa
- Control differential pressure up to an additional 850 kPa
- Controlled filling
- Measures very low flow rates ($\mu\text{l}/\text{min}$).

- Test for performance dependence:

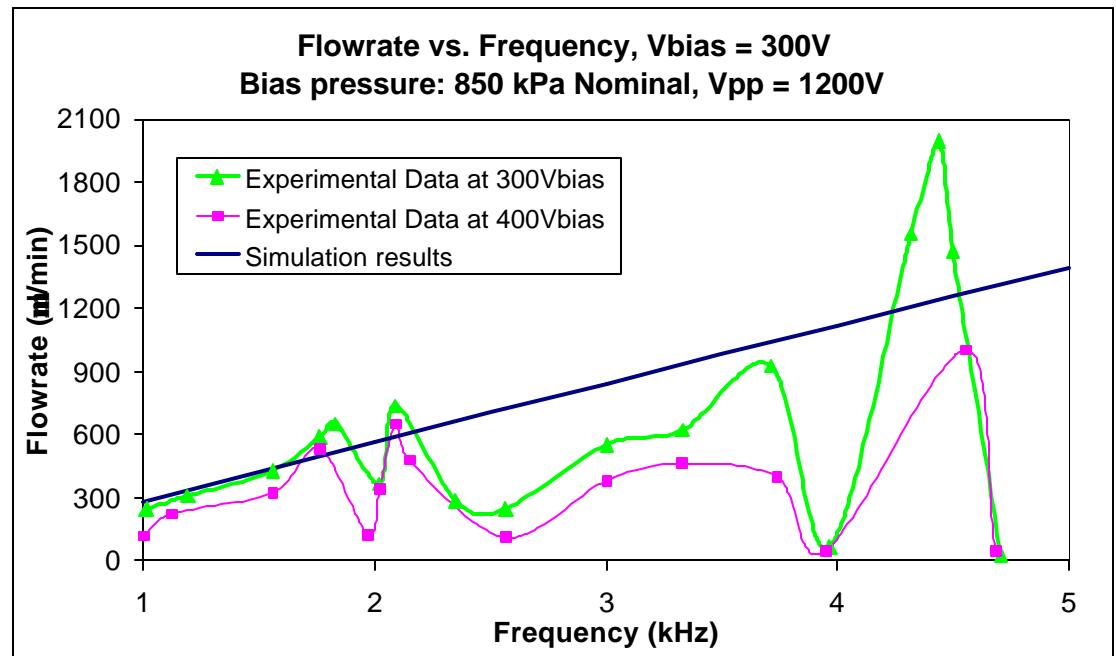
- Frequency
- Peak-to-peak voltage
- Bias voltage
- Pressure differential



Micropump Testing

Frequency Dependence

- Good quasi-static correlation at low frequencies.
- Resonance effects dominate at higher frequencies.
- Rig and packaging geometries influence frequency behavior.



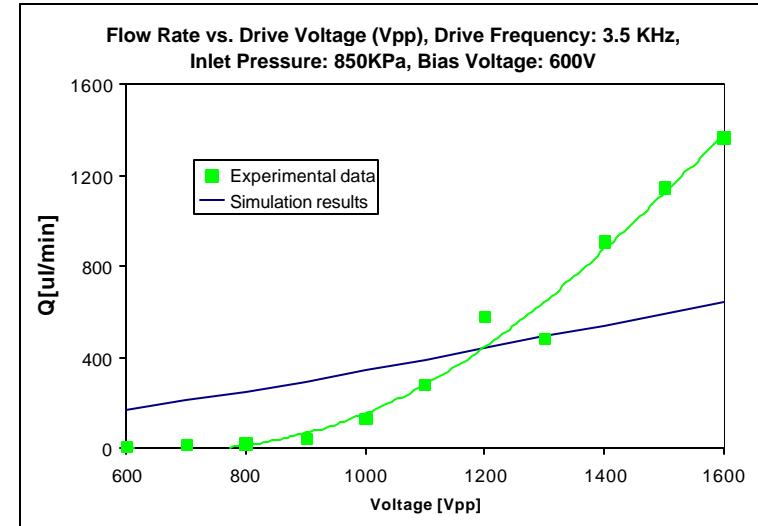
Maximum frequency tested at:
12.5kHz, yielding 2500 $\mu\text{l}/\text{min}$.

Micropump Testing

Drive and bias voltage dependence

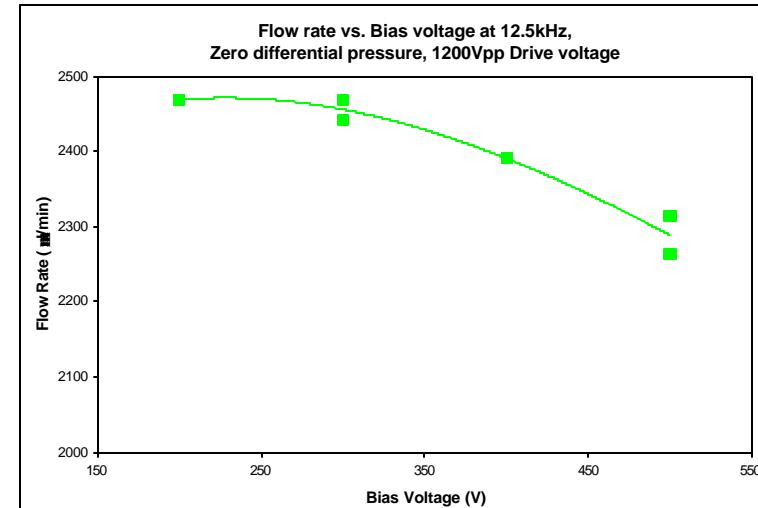
Peak-to-peak voltage dependence:

- Flow rate increases with increasing drive voltage.
- Nonlinear effects



Bias Voltage Dependence:

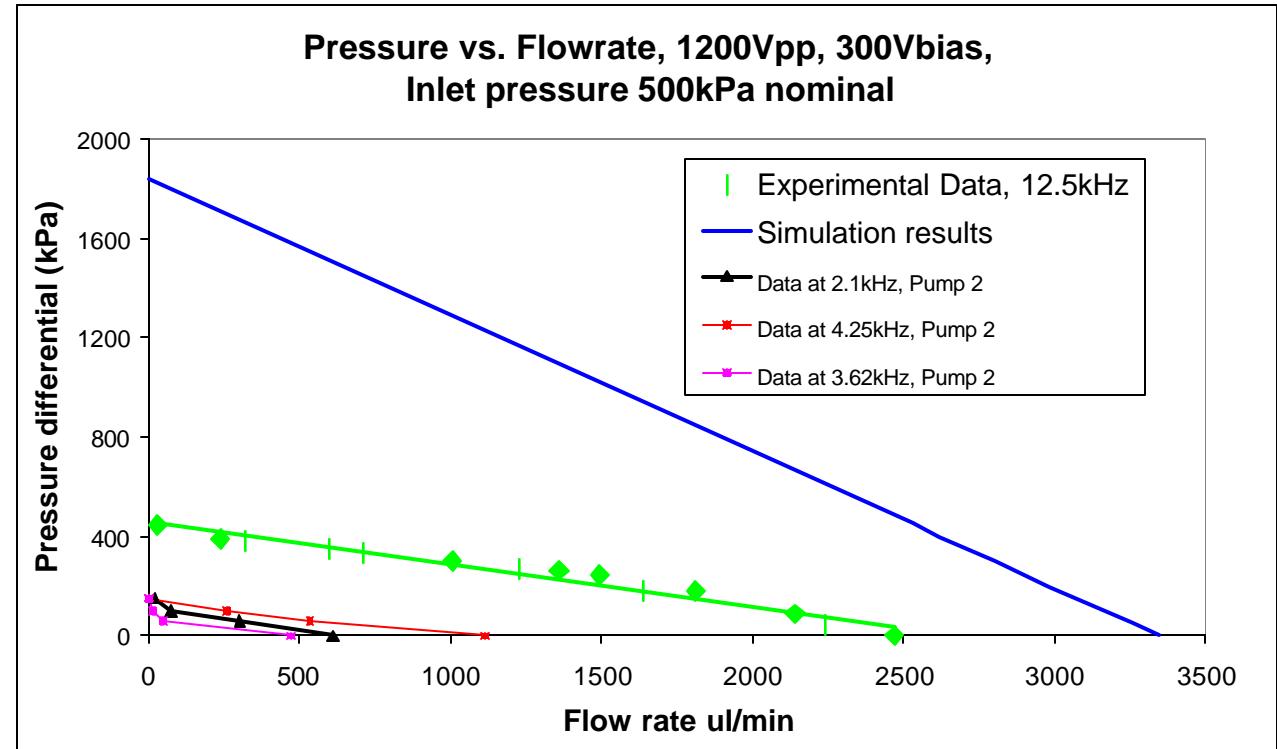
- Model does not account for this behavior.
- Possibly due to manufacturing tolerances.



Micropump Testing

Pressure differential dependence

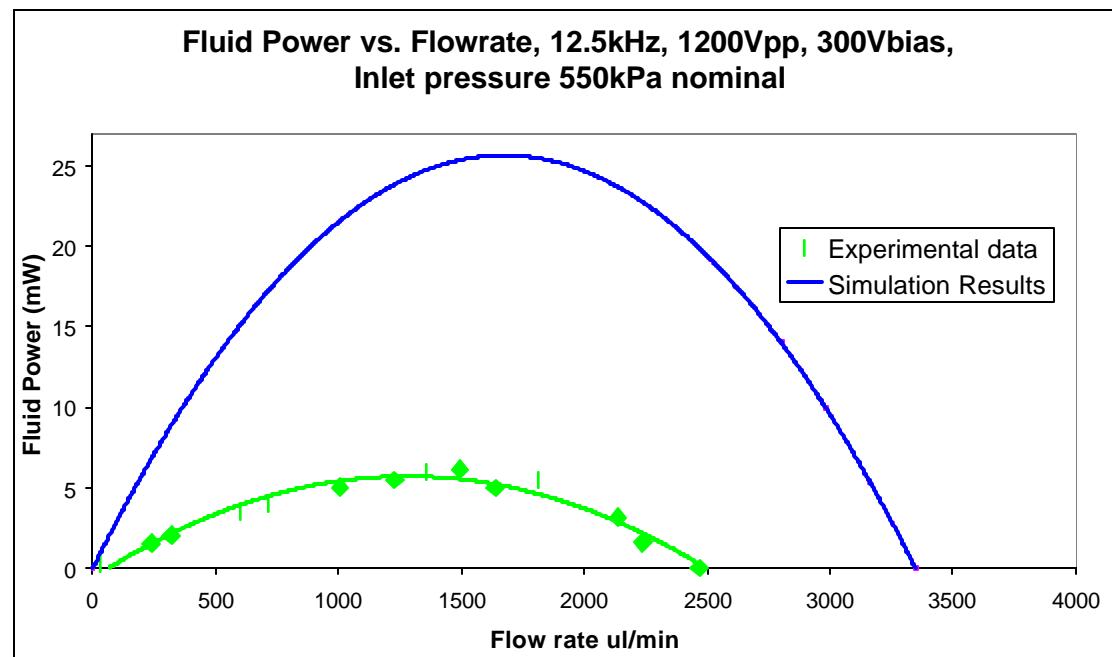
- Best results were obtained at 12.5kHz
- Valve compliance yields reduced performance



Micropump Testing

Fluidic power

- Fluidic Power = $\Delta P \times Q$
- Maximum fluidic power attained: $\sim 6mW$
- Estimated functional mass of $0.3g$ yields a power density of $20W/kg$ compared to a design value of $\sim 85W/kg$

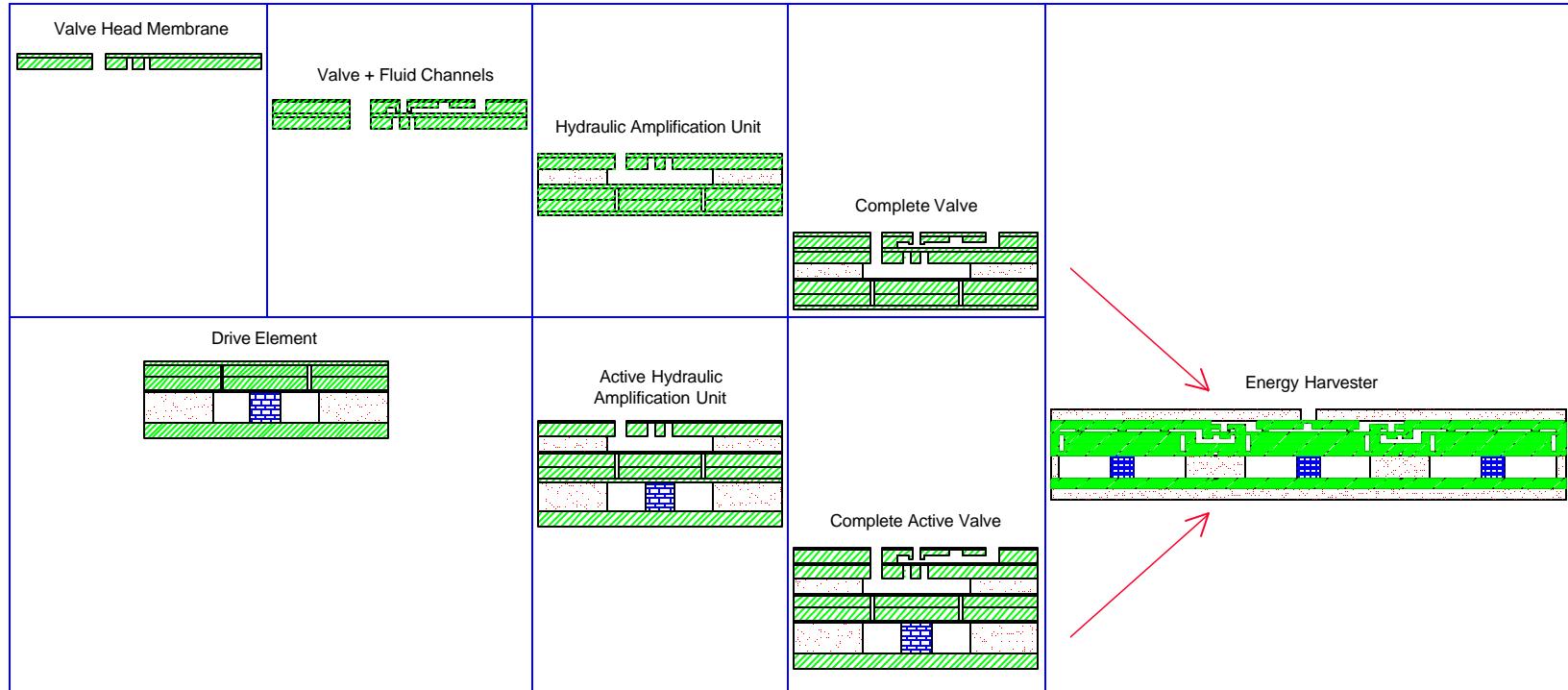


Micropump: Lessons Learned

- Accomplishments
 - multi-wafer fabrication
 - piezo integration
 - fluid filling
- Encouraging simulation/experimental correlation
- Identification of problem areas
 - resonances within experimental test set-up
 - device structural compliances
 - piezo-Si eutectic bonding
 - multiple piezo integration
- Provides solid foundation for development of active-valve energy-harvesting device and active valve micropump

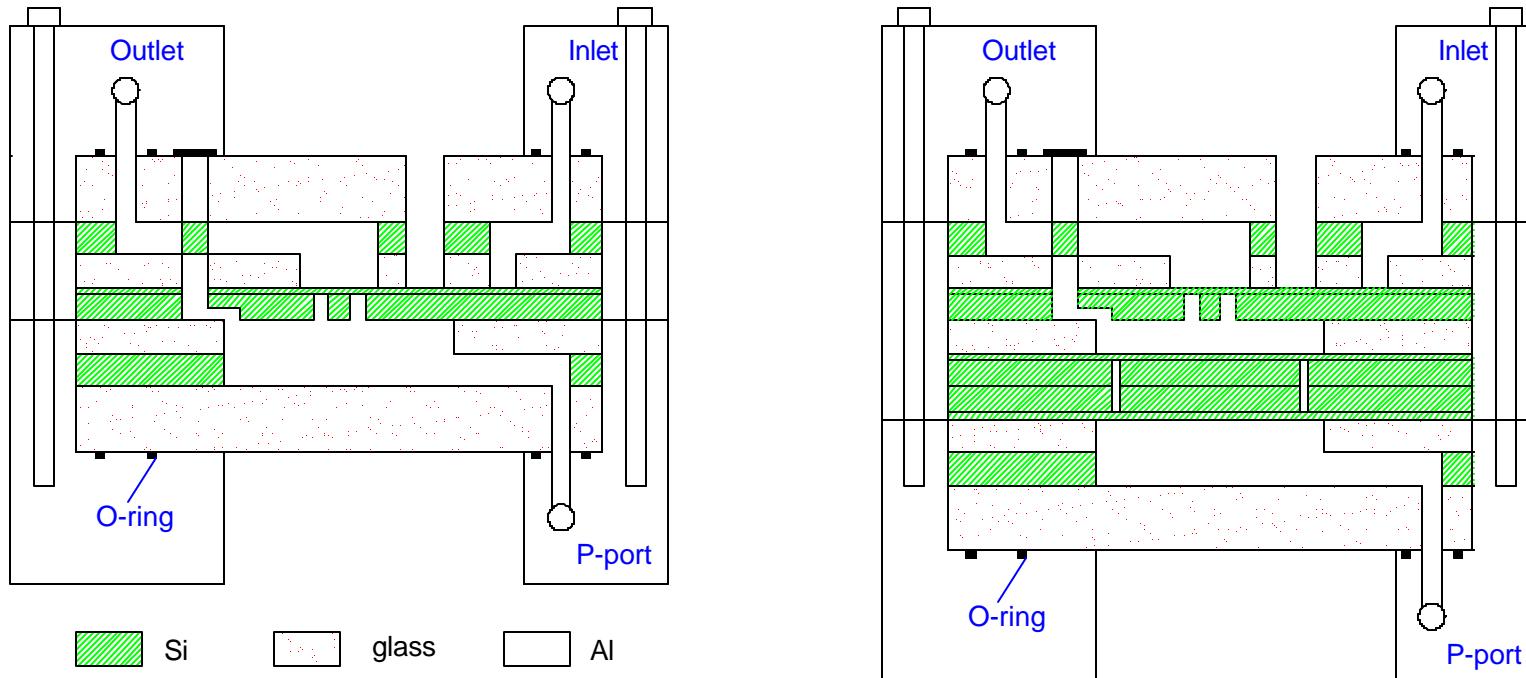
Energy Harvesting Device Program Plan

05/01/2000 06/01/2000 07/01/2000 08/01/2000 10/01/2000 12/31/2000



Test Jig with Glass Windows

(Membrane and Hydraulic Amplification Unit without Piezoelectric Elements)

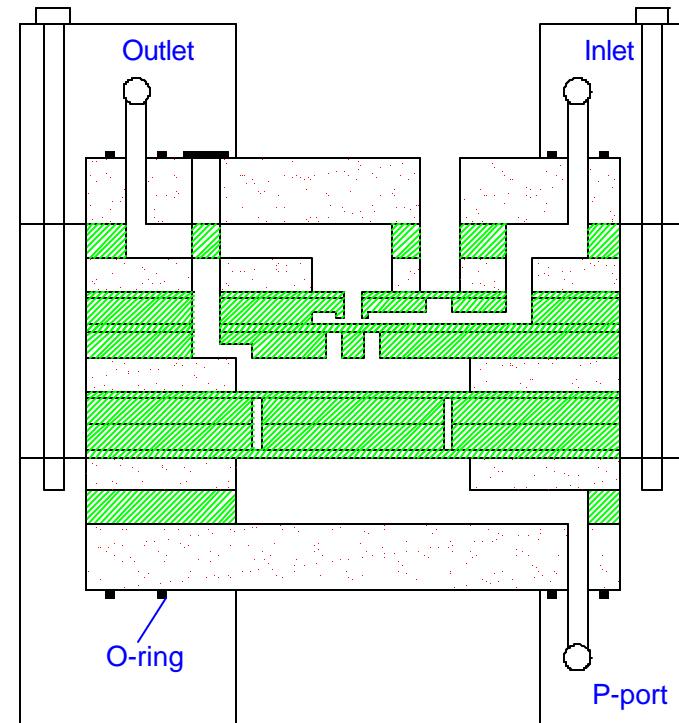
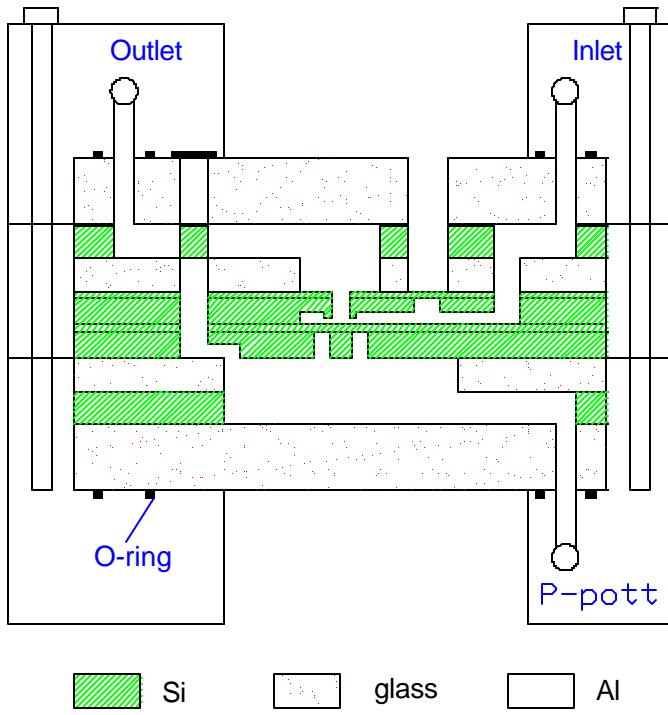


Test jig design requirements:

- Membrane deflections and pressure measured simultaneously;
- All components open to IR camera,
- Modular for all component tests,
- Strong enough and no leaks.

Test Jig with Glass Windows

(Fluid Characterization without Piezoelectric Elements)



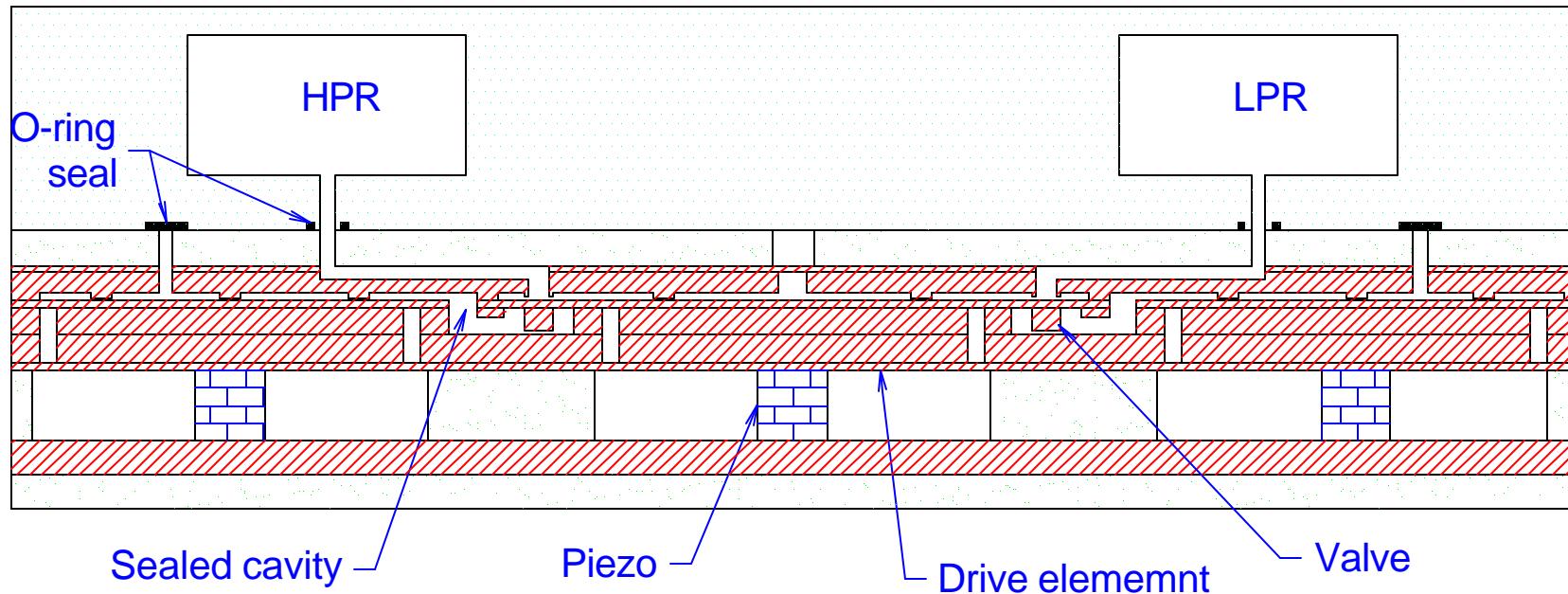
Test jig design requirements:

- Membrane deflections and pressure measured simultaneously;
- All components open to IR camera,
- Modular for all component tests,
- Strong enough and no leaks.

Conclusions

- Micro-Hydraulic Transducer technology offers exciting prospects for very high specific power devices and unique interplay of technologies
- Chip-level 1W Energy Harvesting Device has been designed and simulated:
 - Flowrate = 1.86 ml/s
 - Heel high-pressure reservoir = 2.2 MPa
 - Efficiency = 24.4%
 - Power Density ~ 700-1000 W/kg
- Experimental efforts to date have addressed critical risks:
 - Drive element fabrication/modeling
 - Piezoelectric power generation
 - Fluid filling and pumping
 - Multi-layer wafer bonding
- Many risks still exist
 - Fluid encapsulation
 - High stiffness active valve
 - Further structural miniaturization

Packaging with O-ring Sealing



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